CHAPTER 17

Tooling Process Chains and Concepts

Hans Nørgaard Hansen, Mogens Arentoft, Peter T. Tang,
Giuliano Bissacco and Guido Tosello

INTRODUCTION

Miniaturization has been one of the driving forces of technology during the last 20 years. As predicted by Taniguchi in 1983, by now the technology has moved into the nano-processing era and even for precision machining processes submicrometer precision is achievable [1]. This development has been made very clear in the semiconductor industry during the last 30 years, where the number of components on a chip has been approximately doubled each 18 months. This phenomenon is usually referred to as Moore's law. In recent years the need for micro-mechanical systems has increased, for example in connection with medical devices such as hearing aids, drug delivery systems, lab-on-chip systems, etc. The consequence is that traditional engineering materials such as metals and polymers are seen increasingly more often in micro-products. This requires the development of industrially viable manufacturing methods to support the demand for components and products.

Replication methods such as injection molding and cold forging belong to the preferred choice of macro-scale manufacturing methods when the focus is on mass production and high productivity and yield. The same processes are found in micro-scale manufacturing, now typically referred to as micro-injection molding and micro-cold forging [2]. Special focus on size effects, process characteristics and optimization, etc. has been reported in, e.g. [3–5]. However, a basic prerequisite for process realization is the availability of the tools to be used in the process. For example, the tolerances and dimensions of the tools cannot be scaled down directly, since no methods would then exist for fabrication, i.e. to meet the requirements. Consequently, the choice of processes and their integration into coherent process chains becomes one of the major decisive issues in micro-manufacturing.

Definition of Tooling

A tool is a component that can be used (preferably more than once) to make other components. Normally the tool will be a durable component with a well-defined geometry, but tools that are only used once can be envisaged, for example in casting. In most cases, the tool will be used to fabricate a large number of identical components before it is destroyed due to wear, corrosion and mechanical failure. Tools are essential in replication processes such as hot embossing, injection molding, casting, hot and cold forging, cold forming (punching, stamping, etc.) and so on.

As product features are scaled down, the available technologies for tooling are changed, since traditional tooling technologies such as high precision milling, die-sinking EDM, wire EDM,

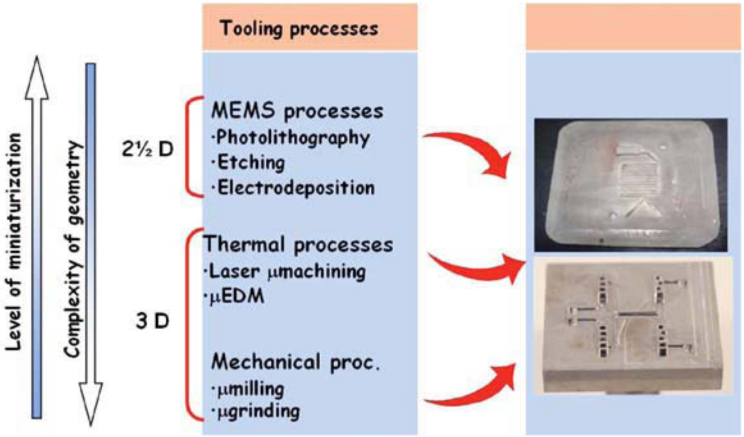


FIGURE 17-1 Example of mold-making technologies in micro-manufacturing.

etc. have lower limits as to the obtainable dimensions and geometries. New precision tooling technologies for potential micro-forming application have emerged as stand-alone technologies (e.g. micro-EDM milling, laser ablation, etc.) but equally interesting are the possibilities that emerge when processes are combined into new process chains. Figure 17-1 illustrates possible technology combinations in mold making for micro-manufacturing. Focus is usually given to the production of the part of the mold actually shaping the micro-part, and this is also the case for Fig. 17-1. However, the integration of such inserts into larger tools actually placed into processing equipment (injection molding machines, presses, etc.) is also of great importance.

Hot embossing and injection molding is usually applied for polymeric materials, while casting, forging and cold forming are applied to metallic materials. In special cases it is possible to produce ceramic components by replication processes, e.g. the hot embossing of glass components is possible at temperatures of from around 550°C and above.

Definition of ‘Process Chain’

In the broadest definition a process chain consists of all of the process steps necessary to produce the part or product in question. This means that a full process chain starts with design, selection of materials and processes, programming or other preparations of the production equipment, actual machining, quality assessment, cleaning, finishing and packaging. If the product consists of more than one component, assembly processes are also included in the process chain (Fig. 17-2).

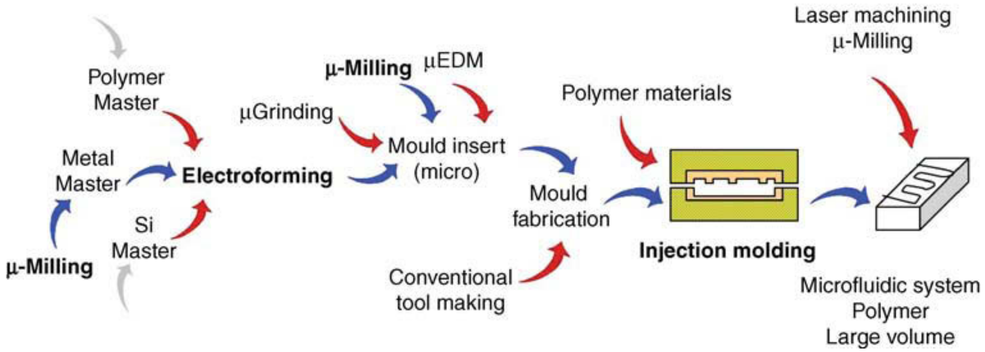


FIGURE 17-2 Possible process chains for the production of a polymer micro-component.

TOOLING CONCEPTS

Utilizing a strictly systematic approach, the possible tooling concepts can be divided into four groups or schemes. The first division is made by identifying the most important shaping process, i.e. the process that creates the shape of the finished tool. This process can either place material on a substrate (additive process) or remove material from a substrate (subtractive process). The substrate is normally a homogeneous material, typically metallic or ceramic (silicon), but it could also be a hybrid material (multi-layered, containing particles or fibers, etc.). The shape of the substrate is typically that of a flat disc or plate, but other simple shapes (rods, spheres, etc.) are also possible.

The second division is made with regards to the way the final tool is obtained. If the tool is fabricated *directly* it is understood that the substrate – after additive or subtractive machining – will become the tool. In the case where the substrate is removed during one of the subsequent steps in the process chain, the tooling concept will be considered an *indirect* one.

Additive processes used in micro-fabrication include:

- electroforming;
- laser sintering;
- physical and chemical vapor deposition;
- printing.

Subtractive processes used in micro-fabrication are:

- milling, turning or other machining processes;
- electrodischarge machining (EDM);
- chemical etching;
- electrochemical machining (ECM);
- laser machining/ablation (alternatively, other beam-processing technologies).

Some of the processes mentioned above require photolithography or other masking methods to define the areas that will be affected (and thus also the areas that will remain unchanged). To a certain extent, lithography can also be considered as belonging to the group of subtractive processes.

The various processes can be combined in almost infinite combinations, but in order to obtain the best and most accurate tooling concepts it is of the utmost importance to consider the various process properties such tolerances and material compatibility (see also selection criteria for tooling process chains).

Material Compatibility

For almost every micro-machining process imaginable, perhaps with the exception of water-jet erosion, the substrate or workpiece material plays an immensely important role regarding the feature sizes, aspect ratios, surface roughness and virtually any other property that can be obtained using the process. Table 17-1 lists some well-known material-process combinations, and some of the typical results that have been obtained in micro-machining.

TABLE 17-1 **Typical Results Obtained using Selected Subtractive Micro-machining Processes and Materials**

Material	Process	Hole Diameter (μm)	Aspect Ratio	Roughness (R_a) (nm)
German silver	Diamond turning	–	–	5
Silicon	Reactive ion etching	10	10	500
Steel	EDM	60	20	500
Aluminum	Milling	50	10	1000
PMMA	CO_2 laser	100	20	2000
PEEK	Eximer laser	20	20	500

TABLE 17-2 Typical Results Obtained using Selected Additive Micro-machining Processes and Materials

Process	Material	Hardness (HV)	Aspect Ratio	Deposition Rate (μm/hour)
Magnetron sputtering	Copper	90	2	2
Electroforming	Nickel	440	2	70
PVD	TiN	1200	0.5	1
Pulse plating	NiCo alloy	580	3	20

Although the subtractive processes are by far the most widely used, the additive processes can in a similar manner also provide very different material properties and results. For some of the additive processes, such as printing and laser sintering, the main geometrical limitations are inherently in the processes themselves. Other additive processes, mainly electroplating (or electroforming) and physical deposition (PVD, CVD, magnetron sputtering, etc.) rely on other (subtractive) processes for the definition of the minimum obtainable feature size and other machining properties (Table 17-2).

For laser-based additive processes the minimum feature size is strongly related to the spot size of the laser beam, which again is interacting with the thermal and optical properties of the material that is being formed (particles sintered together or polymerization of monomers).

Using the physical deposition processes, which are all based on the condensation of materials within a chamber with extreme control of gas flows and pressure, a number of pure metals, alloys, ceramics and semiconductor materials can be deposited. Even with the best magnetron sputtering techniques, the deposition rate is relatively low. The processes are useful for building entire tools or tool inserts. However, the physical-deposition processes are essential for the deposition of hard-wearing resistant coatings, for applying electrically conducting layers on top of insulators and for many other surface-treatment or enhancement steps.

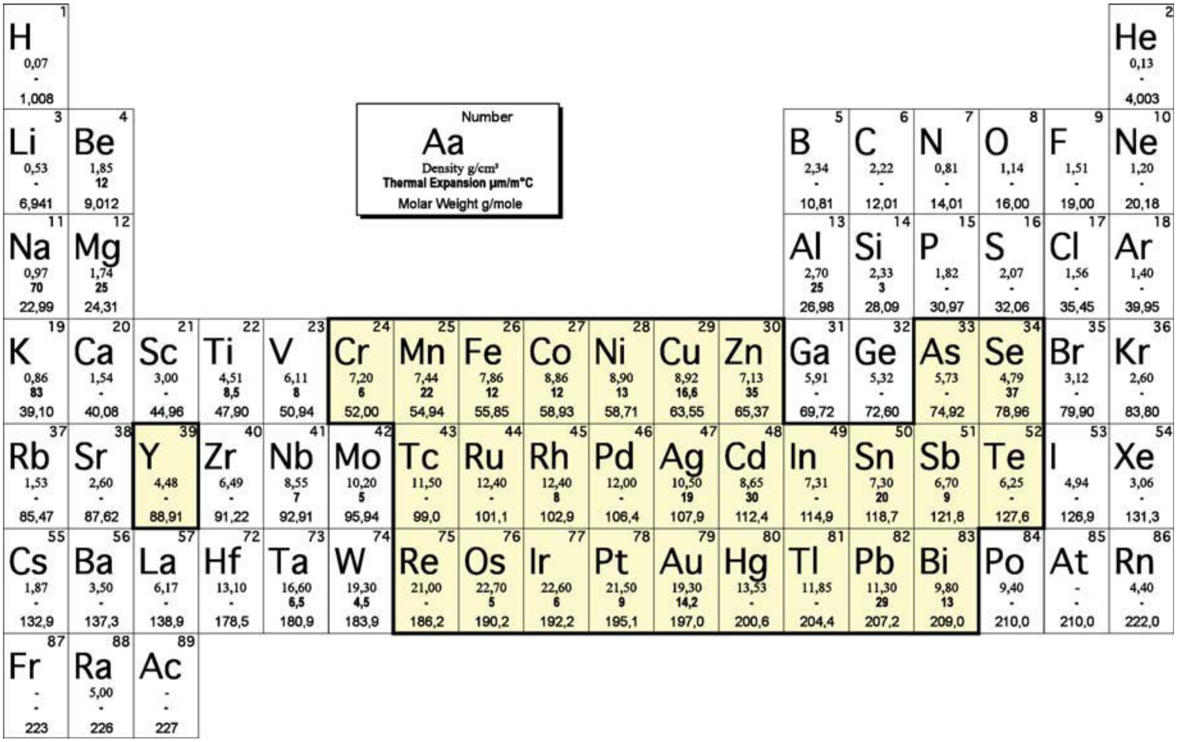
Electrochemical deposition can be divided into two major sub-groups, namely electroplating and electroless or chemical plating. The first group uses an external power supply to generate the electrons needed for the deposition of metal, while the second group utilizes a chemical reducing agent to supply the necessary electrons.

Typical deposition rates for electroplating are from 10 to 400 μm/h. The greatest deposition rates are obtained using highly concentrated sulfamate nickel baths for the deposition of nickel stampers for the manufacturing of optical storage discs (CD, DVD, HD-DVD, Blue-ray discs, etc.). Electroless deposition processes, which can be used for the metallization of non-conductors such as polymers or ceramics, are typically at least ten times slower.

Since electrochemical deposition takes place at relatively low temperature (always below 90°C, and sometimes even at room temperature), the mechanical properties of the deposited materials can be quite different as compared to the values found for forged or molded parts. This is mainly because the grain size of the deposited materials is smaller, due to the low deposition temperature. Materials with small grain sizes (electroless nickel is considered to be amorphous [6]) result in high hardness values and the possibility to reduce the surface roughness of parts machined by diamond turning or micro-milling (Fig. 17-3).

Direct versus Indirect Tooling

Figure 17-4 is a simplified illustration of the four basic process chains for micro-tooling. The result



Number	Aa	Density g/cm³	Thermal Expansion µm/m°C	Molar Weight g/mole
1	H	0,07	-	1,008
2	He	0,13	-	4,003
3	Li	0,53	-	6,941
4	Be	1,85	12	9,012
5	B	2,34	-	10,81
6	C	2,22	-	12,01
7	N	0,81	-	14,01
8	O	1,14	-	16,00
9	F	1,51	-	19,00
10	Ne	1,20	-	20,18
11	Na	0,97	70	22,99
12	Mg	1,74	25	24,31
13	Al	2,70	25	26,98
14	Si	2,33	3	28,09
15	P	1,82	-	30,97
16	S	2,07	-	32,06
17	Cl	1,56	-	35,45
18	Ar	1,40	-	39,95
19	K	0,86	83	39,10
20	Ca	1,54	-	40,08
21	Sc	3,00	-	44,96
22	Ti	4,51	8,5	47,90
23	V	6,11	8	50,94
24	Cr	7,20	6	52,00
25	Mn	7,44	22	54,94
26	Fe	7,86	12	55,85
27	Co	8,86	12	58,93
28	Ni	8,90	13	58,71
29	Cu	8,92	16,6	63,55
30	Zn	7,13	35	65,37
31	Ga	5,91	-	69,72
32	Ge	5,32	-	72,60
33	As	5,73	-	74,92
34	Se	4,79	37	78,96
35	Br	3,12	-	79,90
36	Kr	2,60	-	83,80
37	Rb	1,53	-	85,47
38	Sr	2,60	-	87,62
39	Y	4,48	-	88,91
40	Zr	6,49	-	91,22
41	Nb	8,55	7	92,91
42	Mo	10,20	5	95,94
43	Tc	11,50	-	99,0
44	Ru	12,40	-	101,1
45	Rh	12,40	8	102,9
46	Pd	12,00	-	106,4
47	Ag	10,50	19	107,9
48	Cd	8,65	30	112,4
49	In	7,31	-	114,9
50	Sn	7,30	20	118,7
51	Sb	6,70	9	121,8
52	Te	6,25	-	127,6
53	I	4,94	-	126,9
54	Xe	3,06	-	131,3
55	Cs	1,87	-	132,9
56	Ba	3,50	-	137,3
57	La	6,17	-	138,9
72	Hf	13,10	-	178,5
73	Ta	16,60	6,5	180,9
74	W	19,30	4,5	183,9
75	Re	21,00	-	186,2
76	Os	22,70	5	190,2
77	Ir	22,60	6	192,2
78	Pt	21,50	9	195,1
79	Au	19,30	14,2	197,0
80	Hg	13,53	-	200,6
81	Tl	11,85	-	204,4
82	Pb	11,30	29	207,2
83	Bi	9,80	13	209,0
84	Po	9,40	-	210,0
85	At	-	-	210,0
86	Rn	4,40	-	222,0
87	Fr	-	-	223
88	Ra	5,00	-	226
89	Ac	-	-	227

FIGURE 17-3 Portion of the periodic table showing the elements that can be deposited electrochemically from an aqueous solution [6].

of all four chains is a metallic tool insert, illustrating a simple tool for the replication of a microfluidic pattern.

For the indirect process chains, one particular process is common, and has some special demands on the choice of materials. Indirect tooling, additive or subtractive, always requires – at some point – the separation of the substrate and the almost-finished tool. A complex tool, with micrometer-sized features and high accuracy, is not easy to separate from a substrate using mechanical methods or brute force. Consequently, the gentlest way to effect the separation is to chemically dissolve the substrate. In this case the substrate material should be one that can be dissolved easily and cleanly, without damaging the surface or structure of the tool. There are other ways to effect the separation, such as: melting the substrate, providing a poor but well-controlled adhesion between the substrate and the tool, rapid cooling to enable the differences in thermal expansion to force the two materials apart, and many others.

One of the safest separation processes is to use a simple solution of sodium or potassium hydroxide to secure the dissolution of substrates such as aluminum, zinc or silicon. This can be done cleanly and effectively without damaging tool surfaces of metals such as nickel or stainless steel, which form a passive layer that protects them from dissolution. In the case where aluminum or zinc alloys are used (typically on account of their easier machinability), the various alloying elements (Cu, Mn, Si, Fe, etc.) may create a layer on the tool surface which can be difficult to remove [7] (Table 17-3).

SELECTION CRITERIA FOR TOOLING PROCESS CHAINS

The focus of this section is on tooling for the mass replication of micro-components in polymers,

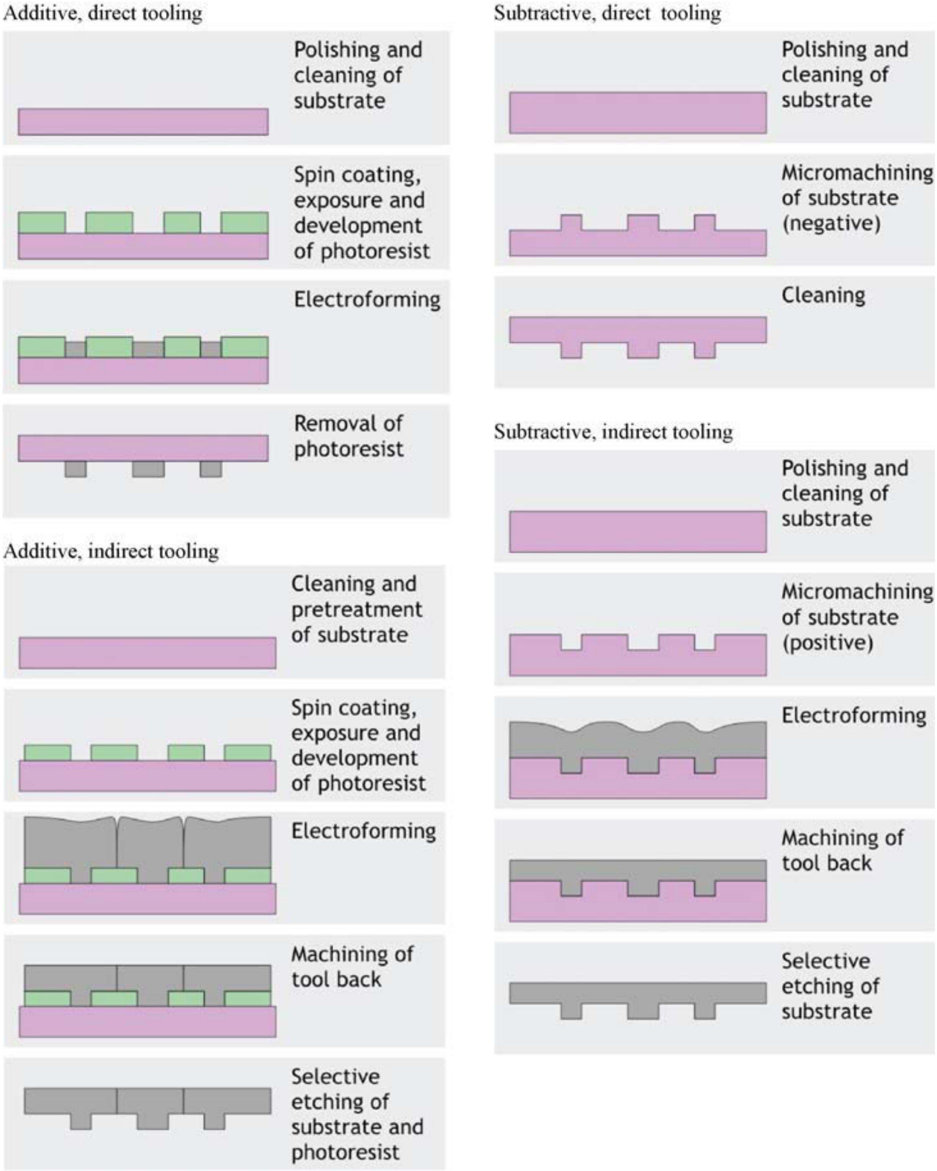


FIGURE 17-4 Schematic presentation of the four basic process chains for micro-tooling.

metals and ceramics. The tools considered are therefore essentially mold inserts, dies, punches, etc. carrying the negative geometry of the part to be produced. Normally micro-replication processes are used for the mass production of micro-components, with production volumes ranging from several thousands to millions of units. However, it is not uncommon in applications where replication processes are used for prototyping in the product-development phase, particularly if the performance of the replication process has a critical influence on the design of the product. Thus the tool requirements will differ substantially, depending on the application.

TABLE 17-3 Chemical Solutions used in Indirect Process Chains for the Selective Etching of Substrates

Name	Conc.	Temp.	pH	Etch Rate (µm/hour)									
(formula)	g/l	°C		Ni	Cu	Au	Zn	Pt	Al	Pd	Cr	Ti	Si
KOH	60	80	>14	0		0	X		X				X
$HCl + HNO_3$		38	<0	X	X	X	X	X	X		X		
$K_2S_2O_8$	25	25		▽	20	0	X	0	X	0	0	0	0
	25	40		▽	30	0							
$(NH_4)_2S_2O_8$	25	25		▽	25	0	X		X	0	0	0	0
	25	40		▽	35	0							
HNO_3	200	25	0.2	5	X	0		0	X	▽	0	0	0
HCl	500	25	<0			0	X	0					
NaCN + NaOH	50 + 30	60	12.0	0	X	X	X						X

Circles mean that the material is not damaged by the etching solution, a triangle means that the substrate is stained or mildly etched and a cross means that it is heavily etched (and eventually completely dissolved). In some cases the etching rate is listed in µm/hour [6].

The main issues influencing the tool requirements are:

- the chosen replication process;
- the production volume and thus the acceptable tooling cost;
- the material of the replicated part;
- the smallest feature size and the complexity (3D surfaces, through-holes, etc.).

For large series production, micro-mold inserts and dies must generally be characterized by high wear and corrosion resistance as well as by fatigue resistance. Except for these general requirements, the characteristics of the tool must match the demands set by the replication process. Hence, while mold inserts intended for polymer replication require a surface hardness of 300–550 HV, dies for micro-forging will require a hardness of above 1000 HV as a consequence of the greater stresses necessary for the plastic flow of the material.

When a mold is produced for prototyping purposes, the surface hardness of the tool falls to a lower level of priority, while the functional performance of the tool and/or process is the main concern. In this case mold inserts can be made in soft metals or alloys, such as aluminum or brass, simplifying tremendously the manufacture of the tool. The complexity of the mold also influences the tool requirements. Tools with simple geometries and large tolerances are relatively inexpensive. In such cases, in the set-up phase of a mass production process, it can be acceptable to change the tool design based on the initial evaluation of the performance of the tool and the process using prototype tools. If, on the other hand, the tool is very complex and the cost associated with producing the geometry is high, redesign iterations must be avoided and the tool will be produced to last for as long as possible, selecting harder materials and setting higher demands on the tool-manufacturing processes.

Once the tool requirements have been defined, a coherent process chain that enables the production of the tool can be selected/defined. It is very important to note that at this point the tool design must not be considered to be rigidly defined. Indeed, based on the capabilities and limitations of the selected/available manufacturing processes, changes in the tool design are allowed in order to ease or improve manufacturing. The redesign (redesign for manufacturing) must of course ensure that the functionality of the tool and of the final part is not compromised.

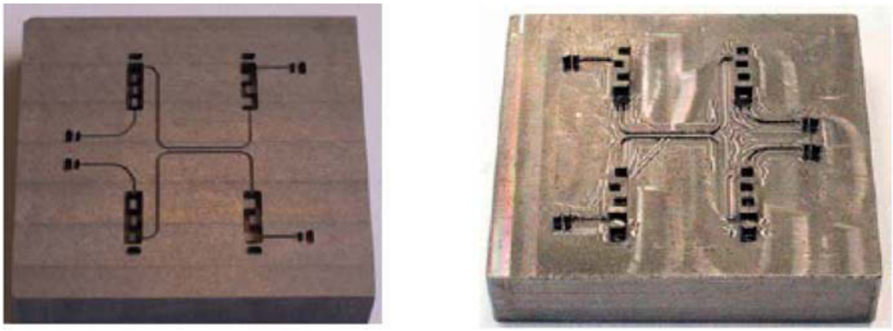


FIGURE 17-5 Micro-fluidic tooling. Aluminum master geometry for subsequent electroforming (left); hardened tool steel insert (right).

In many cases one single process will be able to generate the complete geometry of the part according to the requirements. However, in some cases more complex process chains might be chosen, either because they enable relevant improvements in terms of tool performance or simply because the tool cannot be produced otherwise. An important issue in drafting a process chain is the minimization of repositioning of the mold insert in proceeding from one process step to the next. Each time the insert is moved, alignment errors are introduced, reducing the tolerance window available for the individual manufacturing processes.

On the basis of the defined tool requirements a range of materials can be selected for the tool (mold insert, die, punch, etc.). The material must match the requirements in terms of surface hardness and at the same time allow the manufacture of all features within the prescribed tolerances by means of the available processes. In this respect, it is important to consider that the tool may not need to be machined directly from material having all of the required properties. Indeed, indirect tooling is often a more suitable solution for all those applications where a high surface hardness is not mandatory. Mold inserts for polymer replication show, in general, lower demands in terms of wear resistance and can therefore take advantage of the indirect tooling approach.

Another important point when selecting a tooling process chain is the type of features to be realized and their relationship with the rest of the insert. As many micro-structuring processes are based on material removal (e.g. subtractive processes such as micro-milling, micro-EDM, etc.), the lesser the total amount of material to be removed, the faster will the tool production be completed. Thus when the tool is characterized by small cavities on a relatively large substrate, direct machining of the tool can be an advantage. By contrast, when the tool is characterized by small protrusions that are relatively isolated on a large substrate, indirect tooling is often the best approach, as in this case the machined master (having the opposite geometry to that of the tool) would consist of small isolated cavities on a large substrate (see Fig. 17-5). The two cases considered here represent two extreme configurations, where the convenience of one approach or the other is apparent. There are many intermediate configurations between those two cases, such that the choice of the most convenient approach might not be so evident and other considerations might become determinant. In those cases when additive processes are used for the micro-structuring of the mold or master, the convenience of either the direct or indirect approach with respect to features type is obviously reversed.

Tool requirements and thereby the final tool material, the type of geometry and the type of processes (additive or subtractive) available for the generation of the basic 3D geometry concur in determining the chosen tooling approach (direct or indirect). At this point the most critical choice regards the combination of the specific 3D structuring processes used to generate the insert geometry and their sequence. In selecting the tooling approach an idea of the structuring processes available is of course necessary, as this could be a major limitation and enforce the employment of many of the choices discussed above. The process-sequence selection must be compatible with the limitations of the individual processes with respect to machinable materials, machinable geometries, achievable accuracy, minimum feature size, surface and sub-surface characteristics. The capabilities and limitations of a number of micro-structuring processes with respect to tooling applications will be discussed late. The sequential order of the micro-structuring processes concurring in the generation of the tool must be defined with focus on productivity, minimization of alignment errors and compatibility of the succeeding process steps. In fact, subsequent process steps influence each other in complex ways, originating forward coupling (one process step influences the outcome of the following process steps) and backward coupling (one process step influences the features generated by the previous process steps).

APPLICATIONS

Application 1: Polymer Micro-fluidics

Injection molding or hot embossing of polymer micro-fluidic components is a promising area, but also one of the relatively few areas that can already demonstrate real production capability and commercial applications.

Mainly depending on the required production capabilities, the first thing to decide upon is the replication process. Generally, injection molding is preferred for mass-production applications, while hot embossing is adequate for smaller series and prototyping. In some cases, unusual requirement such as channels widths of below 100 μm, combinations of wide and narrow channels, through-holes, embedded optics, 3D channeling, etc., can change this general perception, since the two replication processes have their own unique features that might be exploitable for a special requirement (Fig. 17-6).

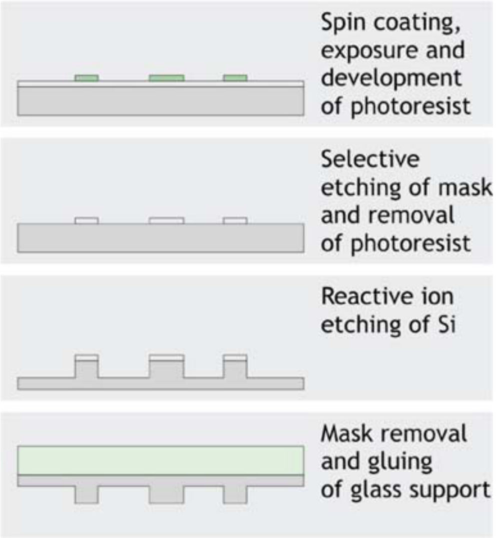


FIGURE 17-6 Process chain for the fabrication of a silicon embossing tool for the manufacturing of a small series of polymer micro-fluidic components.

A more durable tool, compared to the silicon/glass hybrid illustrated above, is necessary for injection molding. In order to be able to produce a metallic tool, and still be able to have channel widths and other features in the 20–40 μm range, an indirect tooling concept based on EDM and electroforming was reported recently [8]

Application 2: Die/Mold Fabrication for Micro-bulk Forming

Different tooling approaches were applied and compared on the basis of a cold-forged industrial micro-component as shown in Fig. 17-7. The component consists of seven diameters and a non-symmetrical geometry at the top. The largest diameter is 3 mm, the smallest outer diameter is 0.6 mm and the length is 3 mm. This component is currently fabricated using cutting. Micro-cold forging is highly attractive, since the productivity can be increased up to 100 times using cold forging compared to cutting. The component must be produced using a two-step cold forging procedure [1].

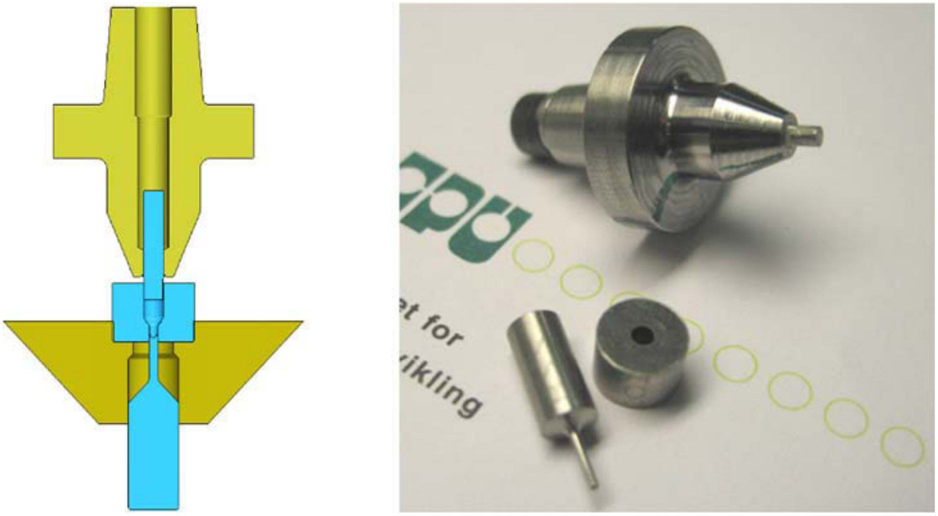


FIGURE 17-7 Direct Die Manufacturing by Micro-EDM Milling.

Two different approaches were followed in order to manufacture the die. The direct tooling approach includes micro-EDM milling. The chosen tool material is a slice of an 8 mm ISO 8020 form B cutting punch made of Vanadis 23 hardened to HRC62-64. By using micro-EDM milling with a 0.3 mm electrode, the die was machined in less than one day. Figure 17.7 illustrates one of the dies.

In the indirect tooling approach, a cathode of aluminum was machined to an outer geometry similar to the inner geometry of the die. A hard nickel alloy is deposited on the aluminum. Subsequently, the aluminum can be etched away, leaving a die with the required inner geometry (Fig. 17-8). The method has been tested with three different nickel alloys. At present, a die with a hardness of 440 HV25g has been tested in the forging of a lead billet. A die with a hardness of more than 800 HV25g is currently being produced. A qualitative and quantitative comparison of the two molds obtained using the two

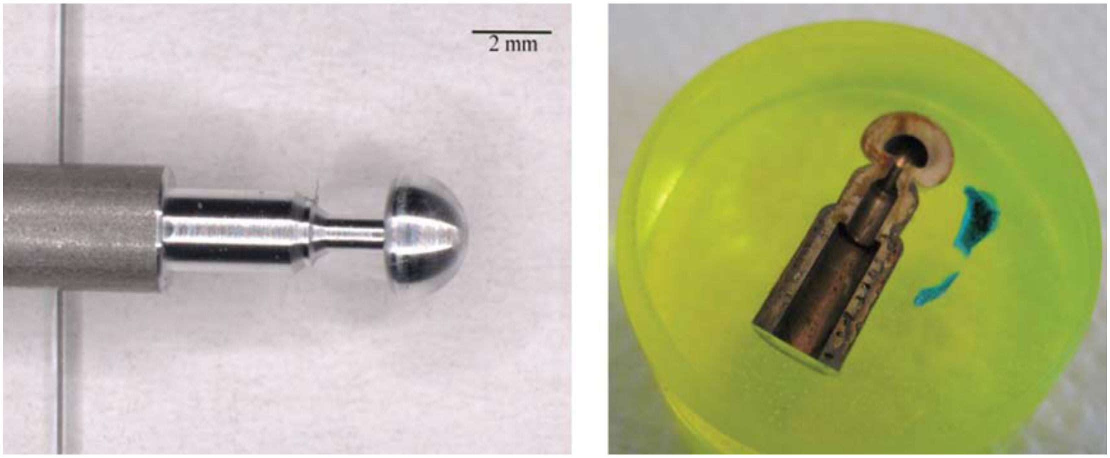


FIGURE 17-8 Indirect Approach for Dies for Micro-metal Forming. Turned Geometry (left) and Cross-section of Electroformed Die (right).

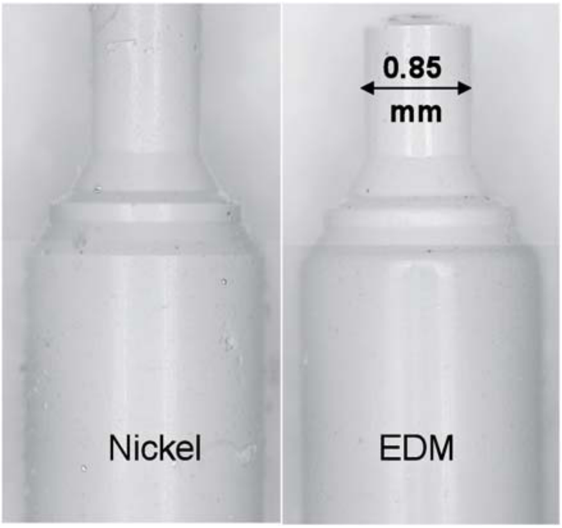


FIGURE 17-9 Replicas of Dies for Micro-metal Forming.

different methods was performed. A silicone replica of the inner geometry of both molds was taken and analyzed by optical methods (Fig. 17-9). It is seen that the EDM approach yields non-sharp corners, whereas these can be obtained in the indirect approach. Furthermore, the dimensions are comparable and within specification for both methods.

CONCLUSIONS

This chapter has introduced the concept of tooling process chains for micro-manufacturing. Two main approaches have been described: indirect tooling and direct tooling. The building blocks of tooling process chains can be combined in numerous ways and obtainable dimensions and geometries are dependent on specific choices of these building blocks. Selection criteria for tooling process chains were discussed and application examples presented.

REFERENCES

[1] N. Taniguchi, Current status in, and future trends of, ultraprecision machining and ultrafine materials processing, Annals of CIRP 32 (2) (2003) 573–582.
[2] L. Alting, F. Kimura, H.N. Hansen, G. Bissacco, Micro engineering, Annals of CIRP 52 (2) (2003) 635–658.
[3] M. Geiger, et al. Microforming, Annals of CIRP 50 (2) (2003) 445–462.
[4] U.R.A. Theilade, Surface micro topography replication in injection moulding, PhD thesis, Department of Manufacturing Engineering and Management, Technical University of Denmark (2005).
[5] U.A. Theilade, H.N. Hansen, Surface microstructure replication in injection molding, The Int. J. of Advanced Manufacturing Technology 33 (2007) 157–166.
[6] P.T. Tang, Fabrication of micro components by electrochemical deposition, PhD thesis, Department of Manufacturing Engineering, The Technical University of Denmark (1998).
[7] P.T. Tang, A method of manufacturing a mould part, WO (PCT) 2006/026989 A1.
[8] G. Tosello, G. Bissacco, P.T. Tang, H.N. Hansen, P.C. Nielsen, Micro tools manufacturing for polymer replication with high aspect ratio structures using μEDM of silicon, selective etching and electroform ing, Microsystem Technology (2008) 10.1007/s00542-008-0564-9.
[9] H.N. Hansen, M. Arentoft, Precision tooling technologies for micro forming, Proc. of the 2nd International Conference on New Forming Technology, Bremen (2007) 157–165.