Chapter 4 Mold Manufacturing

4.1 Machining Methods

Modern tooling machines for mold making generally feature multiaxial CNC controls and highly accurate positioning systems. The result is higher accuracy and greater efficiency against rejects. Nowadays, heat-treated workpieces may be finished to final strength, up to 2000 MPa, by milling. Various operations, e.g. cavity sinking by EDM, can by replaced by complete milling operations and the process chain thus shortened. Furthermore, the thermal damage to the outer zone that would otherwise result from erosion does not occur. Hard milling can be used both with conventional cutting-tool materials, such as hard metals, and with cubic boron nitride (CBN). For plastic injection molds, hard metals or coated hard metals should prove to be optimum cutting-tool materials. Machining frees existing residual stresses which can cause distortion either immediately or during later heat treatment. It is advisable, therefore, to relieve stresses by annealing after roughing. Any occurring distortion can be compensated by ensuing finishing, which usually does not generate any further stresses.

After heat treatment, the machined inserts are finished, ground and polished to obtain a good surface quality, because the surface conditions of a cavity are, in the end, responsible for the surface quality of a plastic part and its ease of release.

Defects in the surface of the cavity are reproduced to different extends depending on the molding material and processing conditions. Deviations from the ideal geometrical contour of the cavity surface, such as ripples and roughness, which increase the necessary release forces.

Competition has recently developed between high-speed cutting (HSC) and simultaneous five-axis milling. HSC is characterized by high cutting speeds and high spindle rotation speeds. Steel materials with hardness values of up to 62 HRC can also be machined with contemporary standard HSC millers. Sometimes, HSC machining can be carried out as a complete machining so that the process steps of electrode manufacturing and eroding can be dispensed with completely. In addition, better surface quality is often achieved, and this allows drastic reduction in manual postmachining.

For the production of injection and die-casting molds, a combination of milling and eroding may also be performed. The amount of milling should be maximized since the machining times are shorter on account of higher removal capability. However, very complex contours, filigree geometries and deep cavities can be produced by subsequent spark-erosive machining. The electrode can, in turn, be made from graphite or copper by HSC.

When machining the part using the CNC machine tool, first prepare the program, then operate the CNC machine by using the program.

1) First, prepare the program from a part drawing to operate the CNC machine tool.
2) The program is to be read into the CNC system. Then, mount the workpieces and tools
on the machine, and operate the tools according to the programming. Finally, execute the machining actually.

### Table 4-1: machining plan form for a part

<table>
<thead>
<tr>
<th>Machining process</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining procedure</td>
<td>Feed cutting</td>
<td>Side cutting</td>
<td>Hole machining</td>
</tr>
<tr>
<td>1.Machining method:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-finish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.Machining tools</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.Machining conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedrate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting depth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.Tool path</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Before the actual programming, make the machining plan for how to machine the part as shown in Table 4-1 and Fig. 4-1. It includes:

1) Determination of workpieces machining range.
2) Method of mounting workpieces on the machine tool.
3) Machining sequence in every machining process.
4) Machining tools and machining

![Fig. 4-1: machining plan for a part.](image)

A CNC machine tool is provided with fixed position. Normally, tool change and programming of absolute zero point as described later are performed at this position. This position is called the reference position as shown in Fig 4-2.

The tool can be moved to the reference position in two ways:

2) Automatic reference position return.

The following two coordinate systems are specified at different locations:

1) Coordinate system on part drawing. The coordinate system is written on the part
drawing. As the program data, the coordinate values on this coordinate system are used.

2) Coordinate system specified by the CNC. The coordinate system is prepared on the actual machine tool table. This can be achieved by programming the distance from the current position of the tool to the zero point of the coordinate system to be set as shown in Fig 4-3.

The positional relation between these two coordinate systems is determined when a workpiece is set on the table.

![Diagram](image)

Fig 4-4: methods of setting the two coordinate systems in the same position

The tool moves on the coordinate system specified by the CNC in accordance with the command program generated with respect to the coordinate system on the part drawing, and cuts a workpiece into a shape on the drawing.

Therefore, in order to correctly cut the workpiece as specified on the drawing, the two coordinate systems must be set at the same position.

To set the two coordinate systems at the same position, simple methods shall be used according to workpiece shape, the number of machinings.

1) Using a standard plane and point of the workpiece. Bring the tool center to workpiece standard point, and set the coordinate system specified by CNC at this position as shown in Fig 4-4a).

2) Mounting a workpiece directly against the jig. Meet the tool center to the reference position, and set the coordinate system specified by CNC at this position. Jig shall be mounted on the predetermined point from the reference position as shown in Fig 4-4b).

3) Mounting a workpiece on a pallet, then mounting the workpiece and pallet on the jig. Jig and coordinate system shall be specified by the same as (2) as shown in Fig 4-4c).

![Diagram](image)
Command for moving the tool can be indicated by absolute command or incremental command as shown in Fig 4-5. The tool moves to a point at “the distance from zero point of the coordinate system” that is to the position of the coordinate values. Incremental command specifies the distance from the previous tool position to the next tool position.

The speed of the tool with respect to the workpiece when the workpiece is cut is called the cutting speed. As for the CNC, the cutting speed can be specified by the spindle speed in min\(^{-1}\) unit.

For example, when a workpiece should be machined with a tool 100mm in diameter at a cutting speed of 80m/min, the spindle speed is approximately 250 min\(^{-1}\), which is obtained from \(N = \frac{1000v}{\pi D}\). Hence the following command is required: S250.

When drilling, tapping, boring, milling or the like, is performed, it is necessary to select a suitable tool. When a number is assigned to each tool and the number is specified in the program, the corresponding tool is selected. For example, when the tool is stored at location 01 in the ATC magazine, the tool can be selected by specifying T01. This is called the tool function as shown in Fig 4-6.

When machining is actually started, it is necessary to rotate the spindle, and feed coolant. For this purpose, on-off operations of spindle motor and coolant valve should be controlled. The function of specifying the on-off operations of the components of the machine is called the miscellaneous function. In general, the function is specified by an M code. For example, when M03 is specified, the spindle is rotated clockwise at the specified spindle speed.

Usually, several tools are used for machining one workpiece. The tools have different tool length. It is very troublesome to change the program in accordance with the tools. Therefore, the length of each tool used should be measured in advance. By setting the difference between the length of the standard tool and the length of each tool in the CNC, machining can be performed without altering the program even when the tool is changed. This function is called tool length compensation as shown in Fig 4-7.

Because a cutter has a radius, the center of the cutter path goes around the workpiece with the cutter radius deviated. If radiuses of cutters are stored in the CNC, the tool can be moved by cutter radius apart from the machining part figure. This function is called cutter compensation as
shown in Fig 4-8.

In control programs, a number following address G determines the meaning of the command for the concerned block. G code list is shown in Table 4-2. G codes are divided into the following two types:

1) One-shot G code. The G code is effective only in the block in which it is specified.
2) Modal G code. The G code is effective until another G code of the same group is specified.

Table 4-2: G code list

<table>
<thead>
<tr>
<th>G code</th>
<th>Group</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>G00</td>
<td>01</td>
<td>Positioning</td>
</tr>
<tr>
<td>G01</td>
<td>01</td>
<td>Linear interpolation</td>
</tr>
<tr>
<td>G02</td>
<td>01</td>
<td>Circular interpolation/Helical interpolation CW</td>
</tr>
<tr>
<td>G03</td>
<td>01</td>
<td>Circular interpolation/Helical interpolation CCW</td>
</tr>
<tr>
<td>G04</td>
<td>00</td>
<td>Dwell, exact stop</td>
</tr>
<tr>
<td>G05.1</td>
<td>00</td>
<td>Al advanced control/Al contour control</td>
</tr>
<tr>
<td>G07.1(G107)</td>
<td>00</td>
<td>Cylindrical interpolation</td>
</tr>
<tr>
<td>G08</td>
<td>00</td>
<td>Advanced preview control</td>
</tr>
<tr>
<td>G09</td>
<td>00</td>
<td>Exact stop</td>
</tr>
<tr>
<td>G10</td>
<td>00</td>
<td>Programmable data input</td>
</tr>
<tr>
<td>G11</td>
<td>00</td>
<td>Programmable data input mode cancel</td>
</tr>
<tr>
<td>G15</td>
<td>17</td>
<td>Polar coordinates command cancel</td>
</tr>
<tr>
<td>G16</td>
<td>17</td>
<td>Polar coordinates command</td>
</tr>
<tr>
<td>G17</td>
<td>02</td>
<td>XpYp plane selection</td>
</tr>
<tr>
<td>G18</td>
<td>02</td>
<td>ZpXp plane selection</td>
</tr>
<tr>
<td>G19</td>
<td>02</td>
<td>YpZp plane selection</td>
</tr>
<tr>
<td>G20</td>
<td>06</td>
<td>Input in inch</td>
</tr>
<tr>
<td>G21</td>
<td>06</td>
<td>Input in mm</td>
</tr>
<tr>
<td>G22</td>
<td>04</td>
<td>Store stroke check function on</td>
</tr>
<tr>
<td>G23</td>
<td>04</td>
<td>Store stroke check function off</td>
</tr>
<tr>
<td>G27</td>
<td>00</td>
<td>Reference position return check</td>
</tr>
<tr>
<td>G28</td>
<td>00</td>
<td>Return to reference position</td>
</tr>
<tr>
<td>G29</td>
<td>00</td>
<td>Return from reference position</td>
</tr>
<tr>
<td>G30</td>
<td>00</td>
<td>2nd, 3rd and 4th reference position return</td>
</tr>
<tr>
<td>G31</td>
<td>00</td>
<td>Skip function</td>
</tr>
<tr>
<td>G33</td>
<td>01</td>
<td>Thread cutting</td>
</tr>
<tr>
<td>G37</td>
<td>00</td>
<td>Automatic tool length measurement</td>
</tr>
<tr>
<td>G39</td>
<td>00</td>
<td>Corner offset circular interpolation</td>
</tr>
<tr>
<td>G40</td>
<td>00</td>
<td>Cutter compensation canccl/Three dimensional compensation cancel</td>
</tr>
<tr>
<td>G41</td>
<td>00</td>
<td>Cutter compensation left/Three dimensional compensation</td>
</tr>
<tr>
<td>Code</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>G42</td>
<td>00</td>
<td>Cutter compensation right</td>
</tr>
<tr>
<td>G40.1(G150)</td>
<td>19</td>
<td>Normal direction control cancel mode</td>
</tr>
<tr>
<td>G41.1(G151)</td>
<td>19</td>
<td>Normal direction control left side on</td>
</tr>
<tr>
<td>G42.1(G152)</td>
<td>19</td>
<td>Normal direction control right side on</td>
</tr>
<tr>
<td>G43</td>
<td>08</td>
<td>Tool length compensation + direction</td>
</tr>
<tr>
<td>G44</td>
<td>08</td>
<td>Tool length compensation – direction</td>
</tr>
<tr>
<td>G45</td>
<td>00</td>
<td>Tool offset increase</td>
</tr>
<tr>
<td>G46</td>
<td>00</td>
<td>Tool offset decrease</td>
</tr>
<tr>
<td>G47</td>
<td>00</td>
<td>Tool offset double increase</td>
</tr>
<tr>
<td>G48</td>
<td>00</td>
<td>Tool offset double decrease</td>
</tr>
<tr>
<td>G49</td>
<td>08</td>
<td>Tool length compensation cancel</td>
</tr>
<tr>
<td>G50</td>
<td>11</td>
<td>Scaling</td>
</tr>
<tr>
<td>G51</td>
<td>11</td>
<td>Scaling</td>
</tr>
<tr>
<td>G50.1</td>
<td>22</td>
<td>Programmable mirror image cancel</td>
</tr>
<tr>
<td>G51.1</td>
<td>22</td>
<td>Programmable mirror image</td>
</tr>
<tr>
<td>G52</td>
<td>00</td>
<td>Local coordinate system setting</td>
</tr>
<tr>
<td>G53</td>
<td>00</td>
<td>Machine coordinate system selection</td>
</tr>
<tr>
<td>G54</td>
<td>14</td>
<td>Workpiece coordinate system 1 selection</td>
</tr>
<tr>
<td>G54.1</td>
<td>14</td>
<td>Additional workpiece coordinate system selection</td>
</tr>
<tr>
<td>G55</td>
<td>14</td>
<td>Workpiece coordinate system 2 selection</td>
</tr>
<tr>
<td>G56</td>
<td>14</td>
<td>Workpiece coordinate system 3 selection</td>
</tr>
<tr>
<td>G57</td>
<td>14</td>
<td>Workpiece coordinate system 4 selection</td>
</tr>
<tr>
<td>G58</td>
<td>14</td>
<td>Workpiece coordinate system 5 selection</td>
</tr>
<tr>
<td>G59</td>
<td>14</td>
<td>Workpiece coordinate system 6 selection</td>
</tr>
<tr>
<td>G60</td>
<td>00/01</td>
<td>Single direction positioning</td>
</tr>
<tr>
<td>G61</td>
<td>15</td>
<td>Exact stop mode</td>
</tr>
<tr>
<td>G62</td>
<td>15</td>
<td>Automatic corner override</td>
</tr>
<tr>
<td>G63</td>
<td>15</td>
<td>Tapping mode</td>
</tr>
<tr>
<td>G64</td>
<td>15</td>
<td>Cutting mode</td>
</tr>
<tr>
<td>G65</td>
<td>00</td>
<td>Macro call</td>
</tr>
<tr>
<td>G66</td>
<td>12</td>
<td>Macro modal call</td>
</tr>
<tr>
<td>G67</td>
<td>12</td>
<td>Macro modal call cancel</td>
</tr>
<tr>
<td>G68</td>
<td>16</td>
<td>Coordinate rotation/Three dimensional coordinate conversion</td>
</tr>
<tr>
<td>G69</td>
<td>16</td>
<td>Coordinate rotation cancel/Three dimensional coordinate conversion cancel</td>
</tr>
<tr>
<td>G73</td>
<td>09</td>
<td>Peck drilling cycle</td>
</tr>
<tr>
<td>G74</td>
<td>09</td>
<td>Counter tapping cycle</td>
</tr>
<tr>
<td>G75</td>
<td>01</td>
<td>Plunge grinding cycle (for grinding machine)</td>
</tr>
<tr>
<td>G76</td>
<td>09</td>
<td>Fine boring cycle</td>
</tr>
<tr>
<td>G77</td>
<td>01</td>
<td>Direct constant-dimension plunge grinding cycle (for grinding machine)</td>
</tr>
<tr>
<td>G78</td>
<td>01</td>
<td>Continuous-feed surface grinding cycle (for grinding machine)</td>
</tr>
<tr>
<td>G79</td>
<td>01</td>
<td>Intermittent-feed surface grinding cycle (for grinding machine)</td>
</tr>
<tr>
<td>G80</td>
<td>09</td>
<td>Canned cycle cancel/External operation function cancel</td>
</tr>
<tr>
<td>G81</td>
<td>09</td>
<td>Drilling cycle, spot boring cycle or external operation function</td>
</tr>
<tr>
<td>G82</td>
<td>09</td>
<td>Drilling cycle or counter boring cycle</td>
</tr>
<tr>
<td>G83</td>
<td>09</td>
<td>Peck drilling cycle</td>
</tr>
<tr>
<td>G84</td>
<td>09</td>
<td>Tapping cycle</td>
</tr>
<tr>
<td>G85</td>
<td>09</td>
<td>Boring cycle</td>
</tr>
<tr>
<td>G86</td>
<td>09</td>
<td>Boring cycle</td>
</tr>
<tr>
<td>Code</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>---------------------------------------------------</td>
</tr>
<tr>
<td>G87</td>
<td>09</td>
<td>Back boring cycle</td>
</tr>
<tr>
<td>G88</td>
<td>09</td>
<td>Boring cycle</td>
</tr>
<tr>
<td>G89</td>
<td>03</td>
<td>Boring cycle</td>
</tr>
<tr>
<td>G90</td>
<td>03</td>
<td>Absolute command</td>
</tr>
<tr>
<td>G91</td>
<td>00</td>
<td>Increment command</td>
</tr>
<tr>
<td>G92</td>
<td>00</td>
<td>Setting for work coordinate system or clamp at maximum spindle speed</td>
</tr>
<tr>
<td>G92.1</td>
<td>00</td>
<td>Workpiece coordinate system preset</td>
</tr>
<tr>
<td>G94</td>
<td>05</td>
<td>Feed per minute</td>
</tr>
<tr>
<td>G95</td>
<td>05</td>
<td>Feed per rotation</td>
</tr>
<tr>
<td>G96</td>
<td>13</td>
<td>Constant surface speed control</td>
</tr>
<tr>
<td>G97</td>
<td>13</td>
<td>Constant surface speed control cancel</td>
</tr>
<tr>
<td>G98</td>
<td>10</td>
<td>Return to initial point in canned cycle</td>
</tr>
<tr>
<td>G99</td>
<td>10</td>
<td>Return to R point in canned cycle</td>
</tr>
<tr>
<td>G160</td>
<td>20</td>
<td>In-feed control function cancel (for grinding machine)</td>
</tr>
<tr>
<td>G161</td>
<td>20</td>
<td>In-feed control function (for grinding machine)</td>
</tr>
</tbody>
</table>

The tool path in Fig 4-9 can be programmed as follow:

1) In absolute programming

```
G92X200.0Y40.0Z0;
G90G03X140.0Y100.0R60.0F300.;
G02X120.0Y60.0R50.0;
```

or

```
G92X200.0Y40.0Z0;
G90G03X140.0Y100.0I-60.0F300.;
G02X120.0Y60.0I-50.0;
```

2) In incremental programming

```
G91G03X-60.0Y60.0R60.0F300.;
G02X-20.0Y-40.0R50.0;
```

or

```
G91G03X-60.0Y60.0I-60.0F300.;
G02X-20.0Y-40.0I-50.0;
```
Fig 4-10 is a program example using tool offset. It can be programmed as follow:

N1 G91 G46 G00 X80.0 Y50.0 D01;
N2 G47 G01 X50.0 F120.0;
N3 Y40.0;
N4 G48 X40.0;
N5 Y-40.0;
N6 G45 X30.0;
N7 G46 G03 X30.0 J30.0;
N8 G45 G01 Y20.0;
N9 G46 X0;
N10 G46 G02 X-30.0 Y30.0 J30.0;
N11 G45 G01 Y0;
N12 G47 X-120.0;
N13 G47 Y-80.0;
N14 G46 G00 X80.0 Y-50.0;
Fig 4-11 is a program example using tool length offset and canned cycles. Offset value +200.0 is set on offset No.11 +190.0 is set in offset No.15, and +150.0 is set in offset No.31.

N001 G92X0Y0Z0;          Coordinate setting at reference position
N002 G90G00Z250.0T11M6;  Tool change
N003 G43Z0H11;            Initial level, tool length offset
N004 S30M3                Spindle start
N005 G99G81X400.0RY-350.0 Z-153.0R-97.0F120      Positioning, then #1 drilling
N006 Y-550.0              Positioning, then #2 drilling and point R level return
N007 G98Y-750.0;          Positioning, then #3 drilling and initial level return
N008 G99X1200.0;          Positioning, then #4 drilling and point R level return
N009 Y-550.0;             Positioning, then #5 drilling and point R level return
N010 G98Y-350.0;          Positioning, then #6 drilling and initial level return
N011 G00X0Y0M5;           Reference, then #6 drilling and initial level return
N012 G49Z250.0T15M6;      Tool length offset cancel, tool change
N013 G43Z0H15;            Initial level, tool length offset
N014 S20M3;               Spindle start
N015 G99G82X550.0Y-450.0  Positioning, then #6 drilling and initial level return
Z-130.0R-97.0P300F70; Positioning, then #7 drilling, point R level return
N016 G98Y-650.0; Positioning, then #8 drilling, initial level return
N017 G99X1050.0; Positioning, then #9 drilling, point R level return
N018 G98Y-450.0 Positioning, then #10 drilling, initial level return
N019 G00X0Y0M5; Reference position return, spindle stop
N020 G49Z250.0T31M6; Tool length offset cancel, tool change
N021 G43Z0H31; Initial level, tool length offset
N022 S10M3; Spindle start
N023 G85G99X800.0Y-350.0 Z-153.0R47.0F50; Positioning, then #11 drilling, point R level return
N024 G91Y-200.0K2; Positioning, then #12, 13 drilling, point R level return
N025 G28X0Y0M5; Reference position return, spindle stop
N026 G49Z0; Tool length offset cancel
N027 M0; Program stop

On the other hand, so far deep hole drilling (gun drilling) has been used more and more widely in injection molds. This method requires a special machine or a deep hole drilling adaptor to another machine, such as a milling machine. The drill operates in a horizontal plane. There are four essential differences from ordinary drilling or milling machines:

1) The stroke of the machine (depth of hole) can be considerably larger.
2) The drill is supported very close to the work piece, as with a drill jig.
3) The cutting edge of the drill is directly, pressure lubricated.
4) The drill works in one pass through solid material. It does not require predrilling.

There are two types of drills, featuring either internal or external chip removal. The external chip removal method is mostly used and is illustrated in Fig. 4-12.

![Fig. 4-12: deep hole drilling in cross section.](image)

1. Gun Drill Material

The tip, at the working end of the drill, is made from a tungsten-carbide alloy, which is much harder and longer lasting than high-speed steel. The head is brazed to a long steel tubing, which is held at its other end in the machine chuck. The tip is about 40 mm long when new; the cutting edge can be reground until the length of the remaining head is not long enough to act as a guide within the hole. The shorter the tip, the more the risk of wandering.

2. Cutting Edge of the Drill

The angles of the cutting lips depend on the material to be cut and are about 300 on the short
lip and 200 on the long lip as shown in Fig. 4-12. This is the most visible difference between twist drills and deep hole drills. There is no chisel edge, but the drill has a very sharp, well-defined V-shaped cutting edge, which spins around the drill center and describes a W-shaped groove, which keeps the drill on center, even when the cutting edge is far inside the workpiece, away from the guide bushing. As the drill progresses into the work piece, the 3/4 cylindrical shape of the head and shank provides a better guide than the very narrow margin on the twist drills. This helps to prevent wandering of the drill.

3. Positioning the Drill

This is done using a method similar to a drill jig. A drill bushing belongs to and is stored with the drill; this bushing guide is fastened to the machine, at the tip of the chip box, which receives the returning coolant and the chips and locates the drill accurately. The face of the guide is held tight against the surface of the work piece so that the coolant with the chips returning through the flute can pass into the chip box without leaking into the open as shown in Fig. 4-13.

![Fig. 4-13: positioning of the gun drill on the surface of the workpiece](image)

4. Cooling of Cutting Edge

The drill has a hole along its entire length through which coolant is pumped at high pressure. The coolant exits right behind the cutting edge. It cools and lubricates the drill for minimum friction within the hole. It also washes the chips out through the open sector of the drill. The chips are then separated from the coolant, which is then filtered and pumped again through the work piece.

5. Effects of Drill Wandering

When drilling two deep holes from opposing sides to create an extra long hole, they may meet only partially. To prevent a flow restriction, the hole depths should be specified so that the holes overlap at least 10 mm at the meeting point. If the deep hole is too close to a surface, there may not be enough metal around it to act as an evenly distributed heat sink, and the coolant is insufficient to remove all the heat generated by drilling. The material will anneal at the side of drilling closer to the surface and cause the drill to wander off in the direction of the surface. Setup of drilling may prevent this from happening by providing an extra heat sink if the surface is flat, e.g., by placing a suitable piece of steel on this surface. A deep hole may also wander off enough and break through into the open, or may weaken the material behind a molding surface or supporting surface. Experience has shown that it is safer to use plates of better grade steel, such as P20 or stainless steels, rather than the cheaper AISI 4140 to avoid catastrophic drilling errors caused by hard spots and resulting wandering drills.

6. Design of Deep Holes

Avoid interrupted cuts. Because the tungsten carbide head is fairly brittle, a gun drill should
always cut into solid material to avoid breaking of the cutting edge. This is not always possible because the channels used in molds do frequently intersect. However, the designer and the machine operator can take certain measures to minimize the risk of damage to the drill. The larger the drill, the easier it is to drill, within reason. Particularly for air lines, if the final hole is small, e.g., 4 mm diameter, the approach holes should be 8 or 10 mm if possible, rather than drilling a very long hole with a 4 mm drill. Avoid offsetting of centerlines of channels. Where the holes meet, there is an interrupted cut; also, the cutting edge finds more resistance away from the centerline of the already existent hole and makes the drill wander off in the direction of least resistance as shown in Fig. 4-14. In a way, this is similar to the drill finding a "soft spot" in the material. For intersecting channels having a large difference in diameter, the small hole must always be drilled first, before drilling the larger hole. Otherwise, the small drill would lose its guidance as it passes through the large hole, as shown in Fig. 4-15. Finally, always locate the entrance of a deep hole so that it can be drilled with standard bushings as shown in Fig. 4-16.

![Fig. 4-14: intersecting channels with offset centerlines cause wandering-off of drill](image)

![Fig. 4-15: small drill loses guidance as it passes through larger hole](image)

![Fig. 4-16: entrances to deep holes should not prevent use of standard bushings](image)

**4.2 Electric-Discharge Machining (EDM)**
Electric-discharge machining is a reproducing forming process, which uses the material removing effect of short, successive electric discharges in a dielectric fluid. Hydrocarbons are the standard dielectric, although water-based media containing dissolved organic compounds may be used. The tool electrode is generally produced as the shaping electrode and is hobbed into the workpiece, to reproduce the contour as shown in Fig. 4-17.

With each consecutive impulse, a low volume of material of the workpiece and the electrode is heated up to the melting or evaporation temperature and blasted from the working area by electrical and mechanical forces. Through judicious selection of the process parameters, far greater removal can be made to occur at the workpiece than at the tool, allowing the process to be economically viable. The relative abrasion, i.e., removal at the tool in relation to removal at the workpiece, can be reduced to values below 0.1%.

This creates craters in both electrodes, the size of which are related to the energy of the spark. Thus, a distinction is drawn between roughing with high impulse energy and planning. The multitude of discharge craters gives the surface a distinctive structure, a certain roughness and a characteristic mat appearance without directed marks from machining. The debris is flushed out of the spark gap and deposited in the container. Flushing can be designed as purely movement-related operation. This type of flushing is very easy to realize since only the tool electrode, together with the sleeve, has to lift up a short distance. The lifting movement causes the dielectric in the gap to be changed. Admittedly, this variant is only really adequate for flat cavities. For complex contours, pressure or suction flushing by the workpiece or tool electrodes would need to be superimposed.

In plain vertical eroding, the eroded configuration is already dimensionally determined by the shape and dimensions of the electrode. Machining of undercuts is not feasible. The introduction of planetary electric discharge machining has now extended the possibilities of the erosion technique. It is a machining technique featuring a relative motion between workpiece and electrode that is achieved by a combination of three movements, vertical, eccentric and orbital. The planetary electric-discharge machining is also known as the three-dimensional or multi-space technique. Fig. 4-18 shows the process schematically.
This technique now allows undercuts to be formed in a cavity. A further, major advantage is that, through compensation of the undersized electrode, it is possible to completely machine a mold with just one electrode.

The electrodes are made by turning, milling or grinding, the mode of fabrication depending on the configuration, required accuracy, and material. High-speed cutting can be used to optimize fabrication of graphite or copper.

Because of the high demands on the surface quality of injection molds and the wear on the electrodes, several electrodes are used for roughing and finishing a cavity, especially for vertical eroding. Thus, microerosion permits a reproducing accuracy of $1\mu m$ and less, with roughness heights of $0.1\mu m$. A mold made by this technique usually only needs a final polishing. In some cases, this is not sufficient, however, e.g. for the production of optical parts or for cavities whose surface must be textured by etching.

In spark erosion, the structure of the surface is inevitably changed by heat. The high spark temperature melts the steel surface and, at the same time, decomposes the high molecular hydrocarbons of the dielectric fluid into their components. The released carbon diffuses into the steel surface and produces very hard layers with carbide-forming elements. Their thickness depends on the energy of the spark. Moreover, a concentration of the electrode material can be detected in the melted region. Between the hardened top layer and the basic structure there is a transition layer. The consequences of this change in structure are high residual tensile stresses in the outer layers that can result in cracking and may sometimes impede necessary posttreatment, e.g. photochemical etching.

Nevertheless, the EDM process has founded a permanent place in mold making nowadays. Some molds could not be made without it. Crucial advantages of it are that materials of any hardness can be processed and that it lends itself to the fabrication of complex, filigree contours.

<table>
<thead>
<tr>
<th>Eccentricity</th>
<th>Manual</th>
<th>As function of Z axis</th>
<th>Automatically controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction of controlled motion R</td>
<td>Z axis</td>
<td>Z axis</td>
<td>Z axis</td>
</tr>
<tr>
<td>Velocity of rotation</td>
<td>Constantly adjustable</td>
<td>Lateral axis dependent on Z</td>
<td>Lateral axis dependent on Z</td>
</tr>
<tr>
<td>Combinations of motions</td>
<td>Process dependent</td>
<td>Process dependent</td>
<td></td>
</tr>
</tbody>
</table>

R-controlled motion

Fig. 4-18: basic movements during planetary erosion
4.3 Cutting by Spark Erosion with Traveling-Wire Electrodes

This is a very economical process for cutting through-hole of arbitrary geometry in workpieces. The walls of the openings may be inclined to the plate surface. Thanks to the considerable efficiency of this process, some cavities are increasingly being cut directly into mold plates as shown in Fig. 4-19.

The metal is removed by an electrical discharge without contact or mechanical action between the workpiece and a thin wire electrode. The electrode is numerically controlled and moved through the metal like a jig or band saw. Deionized water is the dielectric fluid, and is fed to the cutting area through coaxial nozzles. It is subsequently cleaned and regenerated in separate equipment. Modern equipment has 5-axis CNC controls with high-precision positioning systems.

Deionized water has several advantages over hydrocarbons. It creates a wider spark gap, which improves flushing and the whole process. The debris is lower. There are no solid decomposition products and no arc is generated that would inevitably result in a wire break.

Standard equipment can handle complicated openings and difficult contours with cutting heights up to 600 mm. The width of the gap depends on the diameter of the wire a diameter of 0.03 to 0.3 mm. The wire is constantly replaced by winding from a reel. Abrasion and tension would otherwise cause the wire to break. Furthermore, the cuts would not be accurate as the wire diameter would become progressively shorter.

4.4 Mold Surface Finishing and Polishing

4.4.1 Molding Surface Finishing and Symbols

All mold part drawings must show the required finish specifications and any additional
finishing requests such as sand blasting, vapor honing, buffing, etc. Table 4-3 lists many industry finishes and their related manufacturing methods and typical applications.

<table>
<thead>
<tr>
<th>Finish required/μm</th>
<th>Manufacturing method</th>
<th>Specify</th>
<th>Typical application</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>Lapping 8000 diamond</td>
<td>0.025</td>
<td>Petri disk, Optical quality</td>
</tr>
<tr>
<td>0.05</td>
<td>900 stone 8000 diamond Polish</td>
<td>0.05 and buff</td>
<td>Test tube</td>
</tr>
<tr>
<td>0.08</td>
<td>900 stone 3000 diamond Polish</td>
<td>0.08 and buff</td>
<td>Crystal tumbler</td>
</tr>
<tr>
<td>0.10</td>
<td>600 stone 3000 diamond Polish</td>
<td>0.1 and buff</td>
<td>Opaque, shiny surfaces</td>
</tr>
<tr>
<td>0.10~0.20</td>
<td>900 draw stone and vapor hone</td>
<td>0.10~0.20 and</td>
<td>Matte surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vapor hone</td>
<td></td>
</tr>
<tr>
<td>0.10~0.15</td>
<td>900 draw stone and vapor hone</td>
<td>0.10~0.15 and</td>
<td>Semi-opaque Finish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vapor hone</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>600 draw stone 3000 diamond buff</td>
<td>0.2 and buff</td>
<td>General purpose</td>
</tr>
<tr>
<td>0.2~0.3</td>
<td>400~600 stone and sand blast</td>
<td>0.2~0.3 and</td>
<td>Technical product, unspecified</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sand blast</td>
<td>finish</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Texture finish</td>
</tr>
</tbody>
</table>

Even where only one or just a few areas require finishing specifications, symbols and notes are used to indicate the finish, rather than placing written specifications directly on the affected surface. It also may be necessary to show limits for a finished area, as shown in Fig. 4-20.

![Fig. 4-20: finishing symbols on a drawing](image)

a) symbol at surface area and types of notations  b) limitations accompanying finishing notation

If the mold part has several areas that require finishing specs, each surface to be finished will require a symbol pointing at it. The shape of symbols is left to the designer, and the meaning of each symbol must be explained in notes. Many typical symbols are shown in Fig. 4-21. There is no standard meaning attached to these symbols. Each must be explained every time it is used on a drawing. Other shapes may also be used, as long as it becomes clear to which surface they apply.
4.4.2 Special Textures

Textures such as basket weave, leather grain, etc., are usually produced by suppliers specializing in texturing, which is a chemical etching process involving the removal of material from the surface on which the texture is applied. The texture itself is defined by referring to sample chips, identified by names and / or numbers. Unless it is obvious, the designer must specify the area limits of the texture and show the depth of the texture from the surface to which it is applied.

If not properly indicated on the product drawing, Fig. 4-22 shows clearly what can happen. In Fig. 4-22a), the height h of the product includes the texture; in Fig. 4-11b), the texture is added to the height h. Since the depth of textures is usually 0.05 ~ 0.10 mm, or even more, an error in specifying the depth of the etching may affect the product height and appearance significantly, and may lead to scrapping of the mold part.

1. EDM texturing

For texturing, or any other pattern that can be machined into the electrode with EDM, the electrode requires the finish as specified for the molding surface. During the EDM process, the electrode is then sunk into the often already hardened mold steel.
2. EDM finish

This finish is produced by a smooth electrode approaching a work piece with a matching smooth surface. The finish is produced uniformly over the whole area touched by the electrode. The grain of the finish is controlled by the intensity of the current used. To specify and check the finish, comparison chips issued by VDI (a German engineering organization) are used as shown in Fig. 4-23. This is a subjective method of specifying and inspecting, but it is satisfactory for most applications.

Fig. 4-23: comparison chip for EDM finish

4.4.3 Sand Blasting and Vapor Honing

This method of finishing is used after machining and heat treating to impart a dull finish to the molding surface. On vertical or near-vertical molding areas, such roughness may prevent easy ejection.

With products made from low-density polyethylene (LDPE) and a few other plastics (e.g., polyurethane (PU), etc.), ejection is actually improved by some roughness of the molding surface. If a shiny surface is required, buffing after blasting is required. Such roughness wears off with use, and the molds will require occasional roughing of the surface to keep operating without ejection problems.

1. Sand Blasting

Four grades of aluminum oxide grit for sand blasting are commonly used; they are #80 (coarsest), #120, #180, and #240 (finest). Sand blasting is regularly used to remove oxides after heat treat.

2. Vapor Honing

The term "vapor" is actually a misnomer, since no vapor is involved. Very fine "glass shot" is blown with a hand-held nozzle against the molding surface, using compressed air. The process is visually controlled. When the whole surface is matte, the blasting is finished. Areas to be blasted or honed must be clearly defined on the part drawing.
4.4.4 Polishing and Buffing

Polishing is essentially the removal of metal by the action of free abrasive grains carried to the work piece by a tool. The difference between these methods is only the degree of removal. Polishing used to be an "art". Polishers spent many hours polishing every mold component by hand. Today, much is done mechanically, and only parts which, because of their shape, cannot be finished on the mechanical polishing equipment or where the finish is exceptionally fine are done by hand. Note that in general, polishing and honing machines produce more regular (finer, flatter or cylindrical) surfaces, while hand finishing, particularly with unskilled operators, tends to increase waviness or even impart waves to a previously straight, but rough, surface.

1. Why Polish?

   Several reasons for polishing are listed below:
   
   1. Polishing may achieve special optical properties in a product. Will enlight beams pass through the product wall (compact discs, mirrors, etc.), any major unevenness or waviness will distort the light and result in poor performance of the product.
   
   2. Polishing may enhance the appearance of the product. This is the most common requirement in plastic molding. It should be noted, however, that the appearance often is required for the visible outside only. Often, no polish is required on the seen inside of the product, and the finish there need not be better than that required for easy ejection of the product from the mold. For clear plastic products where the inside finish will affect the appearance of the outside, the inside must have the same finish as the outside of the product.
   
   3. Polishing may facilitate ejection. This applies generally to the finish of the core, including side cores. In cases where the product has projections produced by deep recesses in the cavity or where there is little draft angle specified, the cavity must also be free of any roughness that may prevent easy ejection.
   
   4. Polishing may prevent stress risers in a product. Any sharp indent or corner in hardened mold steel, usually created during grinding, will increase the risk of breakage caused by stress concentration. Such corners must be polished to remove the sharp "gouges".

2. Cost of Polishing

   Even with increasing mechanization of the polishing process, there is still a considerable time required to finish a mold. The graph in Fig. 4-24 shows schematically the relation between quality of finish and time required to do it.

   ![Fig. 4-24: plot of quality of finish against time required to product the finish](image)

   It can be seen from Fig. 4-24 that the ideal finish takes infinitely long. The polishing time depends on the skill of the polisher, the quality of finish, the preceding machining operation, and
on the hardness and quality of the material to be polished. Often, the "as machined" surface may be perfectly suitable for appearance of the product and for ejection. It is the responsibility of the designer to specify the minimum finish consistent with operation and product requirements for each mold part. A fine grinding finish or the surface as created by EDM is often all that is required. Too fine a finish may be a waste of money and even be counter productive; also, over polishing may actually destroy a previously flat surface by entering softer areas of the surface and creating waves, called an "orange peel effect".

3. Draw polish

A hand-held felt stick, using the same type of diamond paste as for buffing, is moved over the molding area in the direction of the draw with the work piece stationary.

Ridges and grooves from turning, milling, and grinding in a direction about at right angles to the ejection may create serious problems in ejection, and may even retain and break pieces of plastic in deep grooves. This must be overcome by polishing in the direction of ejection any mold part which could create these problems. Ordinary polishing may smooth down the ridges but still maintain waviness, which affects ejection. Draw polish affects mold performance. Drawings for mold surfaces with minimum draft must specify draw polish, in addition to the finish specified for the product.

4. Diamond Grit

Polishing is the removal of metal by the action of free abrasive grains carried to the workpiece by a tool. The free abrasive agents are usually diamond grit, which is graded by mesh size. Table 4-4 lists grit sizes commonly used for polishing.

<table>
<thead>
<tr>
<th>Grit no.</th>
<th>End-use operation</th>
<th>Range/µm</th>
<th>Mesh approximation</th>
<th>Color guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Super finish</td>
<td>2~10</td>
<td>14000</td>
<td>White</td>
</tr>
<tr>
<td>3</td>
<td>Very high finish</td>
<td>4~12</td>
<td>8000</td>
<td>Yellow</td>
</tr>
<tr>
<td>6</td>
<td>Mirror finish</td>
<td>8~14</td>
<td>3000</td>
<td>Orange</td>
</tr>
<tr>
<td>9</td>
<td>High polish</td>
<td>12~18</td>
<td>1800</td>
<td>Green</td>
</tr>
<tr>
<td>15</td>
<td>Fine finish</td>
<td>12~22</td>
<td>1200</td>
<td>Blue</td>
</tr>
</tbody>
</table>

A hand-held tool with a rotating felt wheel is used to provide the required fine finish, using diamond paste #15, #9, #6 and #3. The work piece may rotate or may be stationary. Buffing has two stages. The first is "cutting down", the refining of a surface by removal of surface imperfections or scratch lines left behind from polishing to make a relatively smooth surface smoother. The second stage is "coloring", a further refinement of the cut-down surface to bring out maximum luster. The penetration of diamond grit with different tools is shown schematically in Fig. 4-25. Fig. 4-26 shows schematically the working of various grits with felt backing.

The amount of material removed from the surface depends on the size of grit embedded in the "tool". As the crystals cut, they rotate and fall away with the metal dust. Grits embedded in a harder matrix, such as wood, copper, iron, or steel, remove more of the mold surface before being shed but are more likely to cause surface scratches.
Fig. 4-25: surface penetration in hardened steel by diamond grit in soft(left), medium (center), and hard (right) "tools"

a) No.9 grit polishing  
b) No.6 grit cutting down  
c) No.3 grit coloring

Fig. 4-26: different grits with felt backing are used for different stages of polishing and buffing

4.5 Electrochemical Material Removal—Etching

For decorative or functional purposes, a surface is very often textured. This is either done for cosmetic reasons, for obtaining a more scratch and wear resistant surface (e.g. leather or wood grain) or a better hand. Flow marks and weld lines can be hidden, too.

The basis of this process is the solubility of metals in acids and salt solutions. Metallic dissolve as a result of potential differences between microregions of the material or between material and etching agent as shown in Figure 4-27. The metal atoms emit electrons and are discharged as ions from the metal lattice. The free ions are used up by reducing processes with cations and anions present in the etching agent. The removed metal combines with anions to form an insoluble metal salt, which has to be removed from the etching agent by filtering or centrifuging.

Almost all steels, without restriction on the amount of alloying elements such as nickel or chromium including stainless steel, can be chemically machined or textured. Besides steel molds, those made of nonferrous metals can also be chemically treated.
The surface finish that can be achieved by chemical material removal or etching depends mostly on the material and its surface conditions and, of course, on the etching agent. Uniform removal is only achieved with materials that have a homogeneous composition and structure. The finer the grain of the structure, the smoother and better the etched surface will turn out. Therefore molds are frequently heat-treated before etching. The depth of heat treatment should always be greater than the depth of etching. If this is not the case, the heat-treated layer may be penetrated. This would result in very irregular etching. Adequate layers are obtained by hardening.

The initial roughness of the mold plays an important role as regards the surface finish after etching. Non-permissible traces from machining are not covered up but remain hazily visible. Before etching, the surface should be well planed with an abrasive. The permissible depth of etching depends on the injection molding processing conditions. The speed of material removal is determined by the etching agent, the temperature and the type of material. It increases with rising temperature.

Basically there are two procedures employed for etching, namely dip etching and spray etching. Both have advantages and disadvantages. With dip etching molds of almost any size can be treated in simple, cost-effective equipment. Difficulties arise from the need for disposing of the reaction products and constantly exchanging the etching agent near the part surface. It is easier to remove the reaction products in spray etching and maintain a steady exchange of the agent on the part surface. The process itself, however, takes considerably more effort and the equipment is more expensive. The etching agent is pressurized and sprayed through nozzles against the surface to be etched. Any masks for areas not to be etched must not be destroyed when hit by the spray, or lifted, permitting the agent to act underneath.

### 4.6 Surface Processed by Spark Erosion or Chemical Dissolution (Etching)

A number of techniques have been developed for masking areas where no material should be removed. They depend on the kind of texture to be applied and range from manual masking to silk-screening, and photochemical means. The last of these allows high accuracy of reproduction to be achieved. The metal surface is provided with a light-sensitive coating, on which the pattern of a film is copied. Fig. 4-28 shows this procedure schematically. A texture made in this way is correct in details and equally well reproducible. Therefore the process is particularly interesting for multicavity molds. A broad range of existing patterns is offered on the market nowadays. With the help of spark erosion and especially photochemical etching almost any desired surface design can be obtained.
Both procedures give mold surfaces a characteristic appearance. Spark-eroded molds exhibit a mostly flat structure with the rim of the discharge crater rounded. Etched surfaces are different. Their structure is sharp-edged and deeper. In both cases the structure can be corrected by subsequent blasting with hard (silicon carbide) or soft (glass spheres) particles and thus adjusted to the wishes of the consumer. With hard particles, the contour is roughened, and with soft ones, it is smoothed.

Each plastics material reproduces the surface differently depending on viscosity, speed of solidification and processing parameters such as injection pressure and mold temperature.

As a rule, the lower the melt viscosity, the greater the accuracy of reproduction turns out. Consequently, materials with a low melt viscosity reproduce a mold surface precisely and with sharp edges. Very mate surfaces that are also mar-resistant are the result. Materials with a high melt viscosity form a more rounded mold surface that is shiny but sensitive to marring. Higher processing parameters, such as mold temperature, injection speed and cavity pressure, reproduce a delicate structure of the mold surface more precisely and give this surface an overall matter appearance. This also means that complicated parts with a large surface and those with large differences in wall thickness show a uniform surface only if the melt is under the same conditions at all places of the cavity.

With this, dimensions and positions of gate and runner gain special significance. Given unfavorable gate position, poor reproduction and increasing shine can be observed in areas far from the gate. The reason for this is that the melt further away from the gate has already cooled and therefore the pressure is too low to reproduce the structure in detail.

Textured surfaces act like undercuts during demolding and they obstruct the release process. Therefore, certain depths dependent on the draft of the wall must not be exceeded during etching or spark erosion. It is important whether the texture runs perpendicular, parallel or irregularly to the direction of ejection. As a rule, the depth of etching may be 0.02 mm maximum per 1° draft.

For spark-eroded molds, the draft x for some materials dependent on the roughness can be
taken from Table 4-5. These values are valid only for the cavities and not for the core of a mold since the molding shrinks onto it during cooling. If it has to be etched at all, the depth must be lower or the draft greater. If the recommended values cannot be adhered to, different mold-wall temperatures should be applied to try and shrink out the molding from the undercut. This can also be accomplished by removing the core first, and allowing the molding to shrink towards the center (e.g. ball pen covers). A precondition for this is a greater draft at the core than at the outer contour.

<table>
<thead>
<tr>
<th>Ra/µm</th>
<th>Draft x(°)</th>
<th>PA</th>
<th>PC</th>
<th>ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>0.56</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.12</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>0.5</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2.24</td>
<td>1.0</td>
<td>2.0</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>3.15</td>
<td>1.5</td>
<td>2.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td>2.0</td>
<td>3.0</td>
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<td></td>
</tr>
<tr>
<td>6.30</td>
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<td>4.0</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>9.00</td>
<td>3.0</td>
<td>5.0</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>12.50</td>
<td>4.0</td>
<td>6.0</td>
<td>5.0</td>
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</tr>
<tr>
<td>18.00</td>
<td>5.0</td>
<td>7.0</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

### 4.7 Laser Carving

Laser carving has advanced to the stage of already being used in preliminary injection molding trials. The beam of a laser is bundled by means of appropriate lenses and focused precisely on the object for machining. A power density of more than 2000 W/mm² is generated at the focal point. This leads to peak temperatures of approx. 2500°C in steel. At the same time, the instantaneous focal point is exposed to a gas atmosphere that has such a high oxygen content that the steel burns spontaneously at this spot. If the beam is now moved along the steel surface, a bead of iron oxide is formed that detaches from the underlying steel surface on account of the heat stress generated. Increasing the power of the laser beam in the focal spot causes the surface beneath it to melt as well. This melt can also be blown away in the form of glowing droplets by the gas jet.

The diameter of the beam in the focal spot and thus the width of the processed tracks is 0.3 mm. A distance of 0.05 to 0.2 mm between tracks is standard. This offset of 0.05 mm yields a surface roughness of Ra of 1.5 µm. This is roughly the same surface quality as yielded by erosion finishing. The cavity is machined layer by layer, the layer thickness usually ranging from 0.05 to 0.2 mm. A special control device ensures that the penetration depth of the beam remains at the predetermined value (e.g. as pre-set by the NC program). Attainable tolerances are 0.025 mm. The particular advantage of this technique is that NC program for guiding the laser beam is obtained directly from the virtual image of a molding or cavity that has been generated by a CAD program and transferred via the stereolithography interface of the CAD system.

This direct way of programming straight from the computer offers for the first time the
possibility of taking tool materials, any kind of alloyed steel of any hardness, other metals and working up the desired shape directly, without intervening material steps. Consequently, this process can be expected to supersede most of the rapid tooling processes developed in recent years. Although the surface quality and the size of the possible cavities do not yet satisfy all demands, it may be expected that this process, when combined with other machining processes such as grinding, eroding, or milling, will satisfy all requirements. The advantages that accrue thereby extend far beyond merely speeding up the process, because it is possible for the first time to use the same material that will be used to mass produce the tool later.

4.8 Electroforming

Thanks to the constant development of electroforming processing, currently in addition to manufacturing cavities used for producing products with high precision, there are large-sized impressions with surface textures like those for the manufacturing of panels.

![Schematic diagram of electroforming cavity](image)

a. steel mold (spindle); b. nickel layer; c. supplementary copper layer; d. cavity to be assembled; e. finished products

Fig. 4-29: schematic diagram of electroforming cavity

As an example of electroforming, Fig. 4-29 illustrates the manufacturing process of a minitype pipette injected impression, where electrode deposits containing nickels are electroformed into a male mold (i.e. spindle) to form a cavity. A male mold which can be made of metals or nonmetals resembles the products whereas the female mold is the contrary of a male mould.

The clamping axis of a male mold may be provided with a plastic protective layer and a metal lead connecting to the negative pole of electroforming solutions, demanding surface treatment on the male mold to prevent nickels from clinging to the surface of the male mould. A metal mold is allowed. However, when plastics (insulation materials) and other nonmetals were employed, an electric conductor should be prepared, which is usually available by employing chemical silver plating technology with the thickness of the silver plated layer \(<0.5\mu\text{m}\) (usually neglectable). After that, be ready to suspend the spindle at the slot of the electroforming solutions. Subjecting to factors like solution components, deposit parameters, current density, solution temperature, pH value etc, it takes 10-15 days to form a nickel layer with 2-4mm thickness. If
necessary, a reinforcing copper layer can be added at a copper solution pool. Subjecting to its surface sizes and other factors, a hard copper layer with deposit thickness as 5-20mm or thicker can be added until meeting the desired outline size.

A finished impression by electroforming remains in the spindle when processing external shapes. The electroformed mold may be separated from the electroformed mold after finishing processing and the cavity can be assembled to a mold when a type is properly selected. Now major merits of electroforming are clear whereas it would be not easy to control the tolerance with electroforming since manufacturing of most moulds including spark erosion requires for cutting or molding operations. In despite of this, depositing in a male mold in the manner of electroforming will not cause any shrinkage and a male mold can be highly precisely reproduced in a mold cavity. Quality and precision in the surface of a male mold determine the quality of the surface of a finished mold and further determine the quality of moulded products therefrom. Manufacturing of modern plastics and related manufacturing processes rely on conditions such as temperature, pressure, injection mode and parting surface. Nickel sulfate solution and nickel sulfamic acid solution are two most frequently used electroforming solutions, which when added with some special additive may in deposition come out with a low stress nickel layer varied in hardness. A nickel layer evenly deposited in thickness at an undulant shape surface can be achieved through improving the diffusion performance of the electroforming solution.

Since working temperature for manufacturing hard nickel cavities in slots with sulfamate solution may be as high as 300 °C, the decomposition of organic additive may cause trouble. Therefore, it is important to be fully aware of which plastic moulding technology to be adopted for a certain cavity so bring full play of nickel and processing method.

Nickel is widely used in electroforming processing since it is an important alloy element in steels with high tension and corrosion resistance. Pure nickel is rarely used in manufacturing mold parts but frequently adopted in anticorrosive coating and decorative coating. Due to its special chemical, physical and mechanical performances, nickel has long been used in various products such as cover of electric shaver, parabola shape mirror surface, compressed container, filter screen, elaborate parts for aviation and making rockets. Thick nickel painting is helpful in repairing worn spare parts in lathe industry. Nickel in plastic processing has the following most conspicuous characteristics:

1. Wear resistance of nickel is nearly the same as that of chrome alloy. Hardness of nickel for electroforming cavity that used for injection of mold is usually around 44-48HRC.
2. Nickel with anticorrosion performance performs well in antioxidation. However, what is more important is that it resists corrosive solutions like hydrochloric acid in manufacturing PVC.
3. Plastic products requires high demoulding capacity while well-qualified electroforming nickel surface has the optimum polishing performance since it is soft and porous free and plastic products can be ejected easily. High passivity of nickel allows much less dosage of releasing agent to facilitate cleaning production and to come out with better surface as well.
4. Elaborate outlines on the model surface such as rubber markings, delicate gem impressions, semi-plain face, plain face and fine machining of mirror surface will be accurately reproduced on the mould.

Such models can be made of metals or nonmetals, as shown in Table 4-6. Metal models with high precision and superior surface quality are usually adopted to electroform and process same impression.
Table 4-6: materials for making male molds

<table>
<thead>
<tr>
<th>Metals</th>
<th>Cold-drawing brass Mx 58, Mx 62</th>
<th>Easy to make and polish, and sensitive to mechanical stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>Steel 1.4300 and 1.4306</td>
<td>Not sensitive to mechanical stress, corrosion resistance, excellent surface quality, and hard to process</td>
</tr>
<tr>
<td>Tool steel</td>
<td></td>
<td>Applicable for making electroformed mold core with fairly thick wall, comparatively small mold core and complicated shapes</td>
</tr>
<tr>
<td>Nonmetals</td>
<td>PMMA</td>
<td>Easy to process and especially applicable for shapes hard to demould</td>
</tr>
<tr>
<td>Other thermoplastics</td>
<td></td>
<td>Current finished products; precisely reproducing cracks</td>
</tr>
<tr>
<td>Spin plastic PVC parts</td>
<td></td>
<td>For spin plastic of moulds for making toys (note the change of sizes)</td>
</tr>
<tr>
<td>Cast plastic epoxy resin</td>
<td></td>
<td>Especially applicable for small &amp; medium-sized moulds, and applicable for those with concave shapes</td>
</tr>
<tr>
<td>Flake epoxy resin</td>
<td></td>
<td>Preferentially applicable for medium &amp; large-sized moulds (reinforcing ribs and bones required, to enhance stability)</td>
</tr>
<tr>
<td>PUR machining materials</td>
<td></td>
<td>Easy to process and mainly applicable for large moulds for airplanes and automobiles. Surfaces with holes shall be sealed</td>
</tr>
</tbody>
</table>

Fig. 4-30: PMMA spindle for small turbines

a) Blank reinforced by steel spindles (separated annealing bar for standard ejection pin)
b) Pre-stressed mold and central line.
c) Spindle processed

![Central line](image)

Fig. 4-31: machining of electroforming blank

d-rotating direction of mill; sr-feed velocity; sk-milling force from inside to outside

Thermoplastic plastics are principally adopted to manufacture products with concave shapes at the side since it is highly difficult to release the mold at such concave places. To illustrate, polymethyl methacrylate (organic glass PMMA) used as moulding materials for turbines may have a diameter as 15 mm as shown in Fig. 4-30. Cast resin is used for reproducing models. Firstly of all, a female mold for cast resin can be produced from the original model and then a
male mold can be produced from the cast resin. This method is also applicable to circumstance when the original moulding material like stone, plaster and leather is poor in anticrosion against electroforming electrolyte. For mold parts with concaves or other special shapes, female moulds are either composed of two or more parts or made of silicon rubber.

Selecting resin with low shrinkage is crucial. The exterior surface layer of a mold shall be made of anticrosive resin free from any filler, hole or black color.

As moulds with high precision dimension and surface quality cost high, in manufacturing small-sized products a layer of black plastics (polystyrene) can be applied to the original mold with brass or steel cores so as to reduce costs of multiple-cavities moulds. Shrinkage of plastics is ignorable since the wall thickness is merely some 1mm.

In order to have high precision in injection moulds, it would be better to process the shape first before moved out from core mould, respectively processing the semi-finished products at the clamps according to the datum levels. Cutters should be rigid. As illustrated in Fig. 4-31, height of the blank forming an impression should be extended to avoid weakness in corners. Redundant materials should be gotten rid off, subjecting to the shape of the blank – brass and nickel be milled or lathed off under same separation conditions at the parting surface.

Steel frame and casting should be carefully matched when electroforming spacers, as electroforming mold itself can not bear any pressure from injection. The spacer should be assembled with the solid moulding parts tightly so that injection pressure may only be braced by impression lining. Any displacement between spacer and impression may lead to breaking up of spacer.

Finished surfaces require little polishing, subjecting to different moulding materials (metal or plastic). Silver painting on impression surfaces should be removed when it is made of plastics, chemical treatment or glass-beads sandblasting recommended.

Electroforming cavity boasts other advantages as well:

1. High precision possible through better control over making male moulds;
2. Free from twisting or deforming (no demand for additional heat treatment);
3. Higher output possible as nickel having favorable thermal conductivity;
4. Absolutely resembled impressions available from one metal mould;
5. Reducing workload in the shop;
6. Easy control over hardness of sediment; e.g. hard nickel - 42~50HRC; nickel sulfamic acid - 20~30HRC; hard copper - 200~220N/mm (equivalent to steel strength as 600~800N/mm).

Electroforming moulds boast evident economical and technical advantages versus other manufacturing approaches of moulds when compared in the injection process. Examples of such products that are unavailable via modern etching and casting are gears and reverberatory mirrors with small mold numbers and high precision requirements, products with concave shapes such as scales, control knobs and keyboards of typewriters, long & thin-shaped products like ball pens, sleeve rods, pen caps, pick-up tubes, etc., and products with natural textures such as natural timbers and leather veins.

Electroforming has its own limits too. Corresponding measures should be taken in terms of a specific defect of electroforming:

1. Highest working temperature of hard nickel limited to some 300~400°C;
2. Deep & narrow slots like grilles for sound-amplifying not easy to make;
3. Electroforming moulds takes long to make since it relies much on depositing speed;
(4) Electroformed moulds from hard nickels being highly sensitive to bending load.

In terms of successful manufacturing of electroformed moulds, we should be fully aware of the characteristic that “the corner is fragile” and know how to control over it. Sharp interior corners and narrow seams are easy to have hairlike cracks along the bisectrix of a corner. Fragile corners always exist regardless of thickness of electroforming sediment. Breaks are likely to exist along such cracks even under light load conditions. As illustrated in Fig. 4-32, this weakness can be eliminated mechanically in the manner of electroforming when brass deposits so as to prolong the service life of impression.

Electroformed impressions made of nickel sulfamic acid can be repaired in the manner of braze welding or other joining method. However, it is not applicable for impressions made of hard nickels since the highest working temperature may reach 300–400°C. In addition to inserting nickel pins, in repairing such impressions an additional electroforming deposit is helpful as well. The affected area may then be repaired until the proper shapes come out.

4.9 Rapid Tooling

Time and cost are becoming more and more important factors in the development of new products. It is therefore extremely important for the injection molding industry to produce prototypes that can go into production as quickly as possible. To be sure, rapid prototyping is being employed more and more often but such prototypes frequently cannot fully match the imposed requirements. Where there is a need for molds that are as close to going into production as possible, rapid tooling (RT) is the only process by which the molds can be made that will enable the production of injection molded prototypes from the same material that will eventually be used for the mass produced part. Such proximity to series production, however, also entails greater outlay on time and costs for this reason. RT will only be used where the specifications require it.

The material additive processes lead fastest to moldings and are therefore the most promising. These also include new and further developments in RP. Examples of such techniques are laser sintering, laser-generated RP and stereolithography, which enable mold inserts to be made directly from a three-dimensional CAD model of the desired mold. RT also covers metal spraying, which has been used for decades in mold making.

Master molding techniques like precision and resin casting may be considered as belonging to RT. These process chains become rapid tooling techniques when an RP technique is used to
produce the necessary master mold.

Whereas, in the techniques mentioned so far, the prototype mold is produced either directly by means of a material additive method or in several processing stages, the so-called hybrid techniques integrate several such stages in one item of equipment. These processing stages are a combination of processes from the other three groups (conventional, master-molding, and material additive techniques). Because hybrid additive techniques combine sequential processes in unit, they can be just as fast as the material additive techniques.

Fig. 4-33 illustrates the general procedure for RT. All methods rely on the existence of consistent 3D CAD data that can be converted into closed volume elements. These data are processed and sliced into layers. 2D horizontally stacked, parallel layers are thus generated inside the computer that, with the aid of a technique such as laser sintering, can be successively created within a few hours without the use of tools or a mold. Furthermore, there is generally no need for supervision by an operative. To an extent depending on the principle underlying the chosen RT method, either a positive pattern (the molding to be fabricated later), or a negative pattern (the requisite mold geometry) is produced. Once a physical positive pattern has been produced, usually any number of moldings may be made by master-molding and coating techniques, which will ultimately lead to a prototype mold after one or more stages. Examples of such process chains are resin casting and metal spraying.

The systematic use of 3D CAD systems during design affords a simple means of generating mold cavities. Most 3D CAD systems already contain modules that can largely perform a conversion from positive to negative automatically.

Once the data have been prepared thus, there are two possibilities to choose from. One is to create a physical model of the moving and fixed mold halves (negative patterns) so as to make a certain number of moldings that will lead to a mold. Metal casting is an example of this. Alternatively, the negatives, perhaps made by stereolithography, may be electrostatically coated.
This process chain is shorter than the molding chain just mentioned. Because the possibilities presented so far involve a sequence of different processes, they are known as indirect tooling. By contrast, direct tooling involves using the generated negative data without intervening steps to produce on an RP/RT system, as is the case with selective laser sintering. Although this is undoubtedly a particularly fast option, the boundary conditions need closer examination. Some of the resultant molds entail laborious postmachining, which is more time consuming.

A major criterion other than subdivision into direct and indirect RT is the choice of tooling material. These are either metallic or so-called substitute materials, the latter usually being filled epoxy resins, two-component polyurethane systems, silicone rubber or ceramics.

4.9.1 Direct Rapid Tooling

The goal of all developments in the field of RT is automated, direct fabrication of prototype molds, whose properties approach those of production parts, from 3D CAD data describing the mold geometry. This data set must already allow for technical aspects of molds, such as drafts, allowance for dimensional shrinkage and shrinkage parameters for the RT process.

A common feature of generative methods for making metallic molds is that the workpiece is formed by addition of material or the transition of a material from the liquid or powder state into the solid state and not by removal of material as is the case with conventional production methods.

All the processes involved here have been developed out of RP methods including selective laser sintering, 3D printing, metal LOM (Laminated Object Manufacturing), shape melting, and multiphase jet solidification or utilize conventional techniques augmented by layered structuring (laser-generated RP, controlled metal build-up).

In selective laser sintering (SLS) of metals, a laser beam melts powder starting materials layer by layer, with the layer thickness varying from 0.1 to 0.4 mm in line with the particle size of the metal powder. The mold is thus generated layer by layer.

Sintering may be performed indirectly and directly. In the indirect method (DTM process), metal powder coated with binder is sintered in an inert work chamber (e.g. flooded with nitrogen). Heated to a temperature just below the melting point of the binder, the powder is applied thinly by a roller and melted at selected sites. The geometry of the desired mold inserts is thus obtained by melting the polymer coating. The resultant green part, which has low mechanical strength, is then heat-treated. The polymer binder is burned out at elevated temperatures to produce the brown part, which is then sintered at a higher temperature. At an even higher temperature again, the brown part is infiltrated with copper at approx. 1120°C, solder alloy or epoxy resin, this serving to seal the open pores that were formed when the polymer binder was removed as shown in Fig. 4-34.
In direct laser sintering manufacture, metals are sintered in the absence of binder. The advantage of not using coated powders is that the laborious removal of binder, and the possibility of introducing inaccuracies into the processing stage, can be dispensed with. Nevertheless, the part must be infiltrated since it has only proved possible so far to sinter parts to 70% of the theoretical density. After infiltration, posttreatment is necessary and generally takes the form of polishing.

Aside from pure metal powders and powders treated with binder, multicomponent metallic powders are used. These consist of a powder mixture containing at least two metals that can also be used in the direct sintering process. The lower melting component provides the cohesion in the SLS process and the higher-melting component melts in the furnace to imbue the mold with its ultimate strength. Candidate metals and metal alloys for direct and indirect sintering are aluminum, aluminum bronze, copper, nickel steel, nickel-bronze powder and stainless steel.

Another way to apply metal is by laser-generated RP. Powder is continually added to the melt in a movable process head. The added material combines with the melted material on the preceding layer. The layers can be added in thicknesses of 0.5 to 3 mm, relative to the work surface, fine beads of metal are formed. The materials used are chrome and nickel alloys, copper and steel. Laser-generated RP is not as accurate as laser sintering and can only generate less complex geometries due to the process setup.

A further development of laser-generated RP is that of controlled metal build-up. This is a combination of laser-generated RP and HSC milling as shown in Fig. 4-35. Once a layer 0.1 to 0.15 mm thick has been generated by laser, it is then milled. This results in high contour accuracy of a level not previously possible with laser-generated RP. The maximum part size is currently 200 mm³ for medium complexity. No undercuts are possible.
Other processes still undergoing development are shape melting and multiphase jet solidification. Both processes are similar to fused deposition modeling, which is an RP process. In shape melting, a metal filament is melted in an arc and deposited while, in multiphase jet solidification, melt-like material is applied layer by layer via a nozzle system. Low-melting alloys and binders filled with stainless steel, ceramic or titanium powder are employed. AS in SLS, the binder is burned out, and the workpiece is infiltrated and polished. However, the two processes are still not as accurate as SLS.

3D printing of metals is now being used to fabricate prototype molds for injection molding. Fig. 4-36 illustrates how the 3D printing process works. After a layer of metal powder has been applied, binder is applied selectively by means of a traversing jet that is similar to an ink jet. This occurs at low temperatures because only the binder has to be melted. Whereas local heating in direct laser sintering can cause severe distortion, this effect does not occur in 3D printing. Once a layer has been printed, an elevator lowers the platform so that more powder can be applied and the next layer generated. The coating is 0.1 mm thick. When steel powder is used in 3D printing, bronze is used for infiltration. Shrinkage is predictable to 0.2%.

Another process being developed for the fabrication of metallic molds is that of metal LOM in which sheets of the same thickness are drawn from a roll, cut out by laser and then joined together. The joining method is simply that of bolting. So far, molds made in this way have only been used for metal shaping and for injection molding wax patterns for precision casting. The advantage of molds joined by bolts is that the geometry can be modified simply by swapping
individual metal sheets.

A variant is a combination of laser cutting and diffusion welding. Unlike metal LOM and most other RT processes, which grow the layers at constant thickness, this process variant allows sheets of any thickness to be used. As a result, simple geometric sections of a mold may be used as a compact segment, a fact which allows RT only to be used where it is necessary and expedient. Possible dimensional accuracy is in the order of 0.1%. Due to the process itself, it is never lower than $\pm 0.1$ mm in the build direction. The tolerances of laser cutting are from 0.001 to 01 mm. Unlike most of the processes mentioned so far, this process imposes virtually no restrictions on part size.

While most direct methods for making metallic molds require posttreatment (infiltration and mechanical finishing), the production of molds from auxiliary materials largely dispenses with this need. Stereolithography (STL) is based on the curing of liquid, UV-curing polymers through the action of a computer-controlled laser. The laser beam traverses predetermined contours on the surface of a UV-curable photopolymer bath point by point, thereby curing the polymer. An elevator lowers the part so that the next layer can be cured. Once the whole part has been generated, it is postcured by UV radiation in a postcuring furnace. STL’s potential lies in its accuracy, which is as yet unsurpassed. Because it was the first RP process to come onto the market, at the end of the 1980s, it has a head-start over other technologies. Ongoing improvements to the resins and the process have brought about the current accuracies of 0.04 mm in the x- and y-axes and 0.05 mm in the z-axis.

The process is originally developed for RP purposes but is also used for rapid tooling of injection molds because of its accuracy and the resultant good surfaces which it produces. When STL is used to make a mold cavity, the mold halves are generated on the machine and then mounted in a frame. Usually, however, the shell technique is employed. In this, a shell of the mold contour is built by STL and then back-filled with filled epoxy resin. The use of the shell technique to produce such an RT mold is illustrated in Fig. 4-37.

Part made by stereolithography feature high precision and outstanding surface properties.
Unlike all other direct methods for making metallic molds, no further treatment is necessary other than posttreatment of the typical step-like structure stemming from the layered build-up by the RP/RT processes. This translates to a considerable advantage time-wise, particularly when the mold surfaces must be glossy and planar. The downside is the poor thermal and mechanical properties of the available resins (acrylate, vinyl ether, eproxy), which cause the molds to have very short service lives. The best dimensional and surface properties are obtained with epoxy resin and the use of particularly powerful lasers makes for faster, more extensive curing of the resin even during the stereolithography process, and this in turn minimizes distortion.

Although STL, has primarily been used for RP, the number of RT applications is on the increase. It is used to make molds for casting wax patterns as well as for injection molding thermoplastics. Such molds serve in the production of parts for a pilot series which can yield important information about the filling characteristics of the cavities. Moreover, it is even possible to identify fabrication problems at this very early stage.

Ceramics are other materials used for direct rapid tooling. They are employed in the 3D printing process described in the previous section as well as in particle manufacturing (droplets of the melted material are deposited by means of piezoelectric ink-jet nozzle). The advantage over metallic molds is the high strength of ceramic molds. This comes particularly to the fore when abrasive, filled polymers are processed.

### 4.9.2 Indirect Rapid Tooling

An RT chain is defined here as a succession of individual molding stages. The use of such a molding chain leads from a master pattern to a cavity that may be used for injection molding. In the sense of this definition, intermediated stages such as machining or simple assembly of already finished cavity modules do not count as individual links in this chain. A good RT chain is notable on the one hand for having a minimum number of molding stages. The lower the number of molding stages, the more accurately the part matches the master pattern and the faster a prototype mold can be made. On the other hand, each RT chain must finish with a cavity that withstands the high mechanical and thermal loads that occur in the injection molding process. The bottom line for all RT molding chains is therefore to have as few links as possible so as to end up with an injection mold whose strength and quality somewhat exceed requirements.

Indirect rapid tooling may be effected with a positive or a negative pattern. While these patterns serve as the master patterns for casting processes, using the virtual CAD negative pattern and new RT process chains can dispense with the master pattern and enable a cavity to be made directly in sand or ceramic slip for casting metals.

Rapid manufacture of prototype molds using the shortest possible process chain frequently involves using RP to make a positive pattern. These patterns can be made by any means, i.e. also conventionally. Casting is frequently employed in the production of prototype molds. This master pattern process entails observing the ground rules for designing cast parts. These include:

- avoidance of accumulation of material.
- avoidance of major changes in cross-section, of thin flanges (1.5 mm minimum) and sharp edges (minimum radius of 0.5).
- avoidance of vertical walls (1% min. conicity).
The simplest, and at the same time a very common process, is that of making a silicone rubber mold, starting from an RP pattern. Once the parting line has been prepared, liquid silicone resin is poured over the pattern in a vacuum chamber. It is not possible to use this type of mold to injection mold prototypes in production material. This process is known as soft tooling since prototypes with certain heat or mechanical resistance can be cast in two-component polyurethane resins. Not only can the Shore A hardness be adjusted to the range 47-90, heat resistance of up to 140℃. This is the only casting method in which the ground rules mentioned above can be largely ignored, due to the use of yielding silicone rubber. Nor is any shrinkage allowance required.

Resin casting is illustrated in Fig. 4-38. The RP pattern is embedded as far as the parting line and fixed in a frame. After delineating, a gel coat is usually applied and cooling coils are incorporated. An aluminum-filled epoxy mold-casting resin is then used for back-filling. When the
molds are being designed, allowance must be made not only for a design suitable for plastics but particularly for shrinkage by the resin.

The coating processes employed are familiar from conventional mold making. They include flame spraying, arc spraying, laser coating, and plasma and metal spraying.

Because both flame spraying and plasma spraying entail temperatures of 3000°C and above, it is necessary to create a heat-resistant positive pattern. For this reason, we shall in the context of rapid production only discuss metal spraying with a metal-spraying pistol. In this process, two spray wires are melted in an arc and atomized into small particles in the presence of compressed air. When the particles impinge on the surface of an RP positive pattern, a liquid film forms that solidifies instantaneously as shown in Fig. 4-39.

The homogeneity of the 1.5-5 mm thick layer depends on the temperature and the distance of the nozzle from the pattern. Since the particles are cooled immediately on contacting the pattern from approx. 2000°C to 60°C, wooden patterns, for instance, may be used in addition to RP materials. A shell made in the way only needs to be back-filled with, e.g., casting resin.

Fig. 4-40 shows another coating method is the electroforming, which has frequently been used in the past for high-quality injection molds. Electroforming is the most accurate method of reproducing surface texture in metal.

The RP pattern is first coated with silver or graphite to render it electrically conducting. In an electroforming bath, individual metals are successively or simultaneously electrolytically deposited, the pattern being coated with the corresponding material. The result is shells with a 4 to 5 mm thick that may be built up of different alloys or metal layers. Electroforming with nickel yields the best results due to such good material properties as high strength, rigidity and hardness, its compatibility with the base material and its good corrosion resistance.
Electroforming reproduces the finest of details, but the part frequently has to remain in electroforming bath for several days. The layer thickness is much more homogeneous than that produced by manual metal spraying. The maximum part size is restricted by the size of the electroforming bath.

![Fig. 4-40: principle underlying electroforming](image)

All of the process chains below begin with the creation of an RP pattern of the mold (virtual negative pattern). To produce a purely metallic prototype mold, several casting techniques may be used in addition to RT. This will often considerably shorten the process chains, as will be demonstrated below.

Of greatest economic importance and hence the most widespread casting technique is that of investment casting, which normally employs patterns of investment wax. The range of possible processes for creating these patterns has been extended by the advent of RT.

It is possible with the aid of selective laser sintering, fused deposition modeling and particle manufacturing to fabricate patterns from investment wax direct. The stereolithography technique, given suitable software, makes it possible to produce hollow-structure patterns. In conjunction with a special illumination technique, these epoxy resin STL parts can be employed as expendable patterns for investment casting. To this end, only the molding shell is built up from the resin and the inner construction consists of a large number of honeycomb-shaped chambers all joined to each other. The density of the mold part is now only 20% that of the solid part, but has excellent strength values and a very good surface finish. Very low internal stresses occur so that the mold is extraordinarily accurate and dimensionally stable. For investment casting, the vent holes of the STL part are sealed with investment wax. During burning out of the STL part, the part gasifies.
almost residue-free. A further possibility is direct production of a gasifiable pattern to produce sintered patterns of polycarbonate. These are sturdier and less heat-sensitive than wax patterns.

All the patterns made like this are surrounded with a ceramic coating. This is achieved by immersing the pattern into a ceramic bath and subsequently converying it with sand. This process is repeated until the desired coating thickness of the refractory ceramic shell is achieved. After this, the mold part must dry before it is burned in excess oxygen at 1100 °C. During firing, the master pattern gasifies and so the corresponding materials can then be cast in the resultant ceramic mold. After drying, the ceramic body is smashed to yield the desired part. It is important for the quality of the cast part that the wax pattern be totally and uniformly wetted when first immersed in the ceramic bath.

Since the cast material shrinks on cooling down in the ceramic mold, the master pattern must be correspondingly larger than the original. Additionally, shrinkage in each RP process employed, as well as of the ceramic shell, must be considered. Distortion of the mold shells must also be expected, and must be rectified. Prototypes made by investment casting can accommodate high load, have a high workpiece accuracy and good surface quality. A serious disadvantage of the process is the long drying time of the ceramic shell of up to one week.

Investment casting is used for making metallic prototype molds, inserts and metallic pilot parts. The process is particularly suitable for cylindrical cores.

The process chain of investment casting can be shortened considerably by the application of 3D printing. In this case, a virtual negative pattern is required instead of a physical negative one. The 3D printing process described above thus allows direct production of the ceramic shell. This is referred to as direct shell production casting (DSPC). Pouring in the metal and deforming are the only steps necessary.

As investment casting, evaporative pattern casting employs expendable patterns that remain in the mold and evaporate without residue when the hot metal is poured in. Very high accuracy can be achieved with this technique.

A one-part, positive master pattern of a readily evaporative material (EPS foam) is modeled in sand. After compaction of the sand, high-melting metal can be poured directly into the mold. The gas produced by decomposition of the pattern can escape readily because the sand is porous. A material frequently employed in the field of RT is the light metal Zamak, a zinc-aluminum-copper alloy that is easy to posttreat.

A sinter process which still requires upstream molding steps is the Keltool technique. In this process, unlike the process chains described above, a higher strength copy of a mold pattern is made. The goal here is to convert patterns made of a low-strength RP material into metal parts. To prepare an injection mold, a pattern of the mold half is generated first by any RP process. As in the silicone casting process, a highly heat-resistant RTV silicone that can be demolded after curing is poured around the master pattern as shown in Fig. 4-41. An epoxy binder that is very highly filled with a metal alloy in powder form is then poured into this mold.
The result is a stellite green part of the cavity to be made. As with selective laser sintering, the binder is thermally desorbed, and infiltration performed, with the polymeric binder being replaced by copper/zinc (Cu/Zn) alloy. The surfaces can then be machined.

Finally, an overview of all the processes discussed here is presented for comparison purposes. Many of the metallic processes are not yet commercially available on the market. Only selective laser sintering, metal spraying and electroforming are available. The Keltool process is also available. Aside from complexity and stability, however, major criteria are attainable surface quality, the availability and the price, which can vary extensively according to geometry.

### 4.10 Mold Lifting

Safety must be a primary consideration of the mold designer. How can a mold, or any heavy mold part, handled safely? No person should repeatedly lift parts heavier than 20kg or any part which is awkward to handle, regardless of weight, without some mechanical assistance, such as a hoist.

Not only should nobody get hurt when handling a mold or mold part, but the mold maker has a legal responsibility for any accident that may arise because of an omission or poor design. Where it is not possible to provide a suitable safety feature, at least a clearly visible warning label or name plate must be provided to inform of the possible hazard and its consequences.

There are four situations during which part or all of the molds is handled.

1. Machining a mold part (plates, heavy cavities and cores).
2. Assembling the mold (servicing and maintenance).
3. Mounting the mold in a machine.
4. Operating the mold.

During the design phase, the designer must try to foresee how a mold or mold part will be handled or mishandled. Where the handler, for example, the machinist, assembler, or molding
technician, may cause injury to himself or the others. The designer must consider in all case show size, location, and number of tapped holes in general and for handling devices will affect the strength and the fatigue life of the part.

From the onset, a block for any heavy mold part usually including plates, cavities and cores must have one or more threaded holes to permit the machine operator to utilize eye bolts and a hoist for handling as shown in Fig. 4-42. Lifting with eye bolts is preferred to lifting with magnets, particularly when lifting a finely ground plate, which could be scratched when using a magnet.

![Fig. 4-42: Lifting hole (LH) location above center of gravity (CG) in a plate for handling](image)

The location of these holes can only be determined at the completion of the mold design, after the location for all necessary heating and cooling channels and mounting holes and the shape of the mold part are finalized.

It is usually best to provide the handling holes as close as possible above the center of gravity (CG) of the heavy part while avoiding an area which is already occupied by holes, channels, etc. as shown in Fig. 4-43. It is important that these holes do not weaken the cross section of the mold part by reducing its wall thickness or by creating stress risers, which are unavoidable with tapped holes.

![Fig. 4-43: lifting holes near center of gravity but away from weak area of thin wall](image)

It is sometimes impossible to reconcile both above-mentioned conditions, and a compromise will be required. The compromise may be that the lifting hole is not exactly above the CG, and the part may not hang squarely when handled, or it may be that two or three holes are provided in such a way that a chain can be utilized to connect two or three eye bolts, with the hoist attached to the center point, to provide an approximate location above the CG. Usually, plates will be handled and lifted from more than one side. There must be lifting holes on all edges to accommodate lifting of the plate as shown in Fig. 4-44.
There are basically two reasons for placing lifting holes on the face of a plate:

1. The work piece is cut out in its center to such an extent that a lifting magnet can not touch on a large enough area to hold the plate safely. The diameter of a magnet is usually between 250-300 mm. This applies specifically to large rings or to large plates.

2. All heavy plates should have lifting holes in the largest plane portion of the plate, unless there are already suitably tapped holes in the face required in assembly of the mold.

The holes should be placed symmetrically about the CG and are best located on the centerline of the longer axis of the part as shown in Fig. 4-45. The exact location of the two holes for lifting can only be determined after the plate is completely designed, to ensure that these holes do not interfere with other features of the plate.

As a rule, all plates over 50 kg mass must have lifting holes. If possible, lifting holes should be located so that they are not covered by other components and can be used for lifting even after the plate is partly or completely assembled.

Attention to these rules is particularly important if the applied load approaches the rating of the eye bolt.

1. Eye bolts must never be ground, machined, stamped, or marked with a sharp tool or instrument.

2. The receiving threaded hole should be countersunk and/or counterbored, or a spacer washer should be used as shown in Fig. 4-46. Ensure that at least 90% of the threads are engaged in the threaded hole.

3. Ensure that the eye bolt is screwed down all the way and is properly seated. The shoulder should bear firmly against the mating plate surface or a spacer washer.

4. Loads should always be applied in the plane of the eye, not at an angle to this plane.

5. Never exceed the recommended capacity of the eye bolt.

6. Do not paint, plate, or galvanize an eye bolt. This could easily hide flaws and/or affect fits.

7. An inspection program for eye bolts should be established and implemented on an ongoing
basis. To ensure safety, all such equipment must be regularly checked for possible stress signs, cracks and wear. Each item should be identified by number, type, etc., and a report on its state be made periodically. Questionable items must be discarded, not repaired.

a) Hole is countersunk. b) Hole is countersunk c) A spacer washer is used. and counterbored.

Fig. 4-46: seating the eye bolt shoulder against the load.

Fig. 4-47: lifting holes in core and in stripper ring.

Fig. 4-48: lift bar used to handle the mold part.

Lifting holes must also be provided for handling of other items if they are heavy, and in particular if they must be removed for servicing while the mold is in the machine. This applies to cavities, cores, and locking and stripper rings. Each of these elements must have at least one lifting hole above the CG. Also, an assembly should have a lifting hole, if possible. Of course, it could coincide with a part lifting hole as shown in Fig. 4-47. The designer must ensure that such lifting holes will not weaken the part excessively, particularly in the case of a ring-shaped part. The location of lifting holes in mold parts other than plates needs the same considerations as outlined for lifting holes of a plate, and is the responsibility of the mold designer. If the CG is not through an area where a tapped hole can be installed, a lift bar may be required for handling of the
part. A lift bar as shown in Fig. 4-48 must be shown on the assembly drawing, and must be identified with its own part number and the mold number. This is important, because it will be used only when servicing the mold, and the molder may store it remotely from them old and would otherwise have difficulties identifying the proper lift bar when needed. There must be a name plate on the mold shoe to advise that the lift bar is to be used for safe handling of this assembly.

![Fig. 4-49: lifting holes before (LH1) and after (LH2) machining in a heavy core.](image1)

![Fig. 4-50: lifting holes before (LH1) and after (LH2) machining of an ejector box.](image2)

A work piece which had a lifting hole above the CG before machining may have a different CG once the plate is finished, after substantial amounts of material have been removed from one face of the plate as shown in Figures 4-49 and 4-50. The new CG is more important for the next stage of manufacturing and assembly, where square handling of the parts will facilitate work. It is, therefore, preferable to determine the location of the CG of the finished part rather than the blank, and locate the lifting hole(s) above it. Otherwise, the plate or part may hang at an angle during handling after machining the bulk of material. Once several plates, each with its own CG, have been assembled, the resulting CG of the assembly will probably be at a new location. To achieve square handling of the assembly, a new lifting hole may be required. The exact location of the new CG can easily be calculated, once the average weight of each part has been estimated and the location of the CG for each component has been established.

### 4.11 Process Planning and Workshop Scheduling

On the basis of process planning and production scheduling, a multiplicity of design process operation are sent down to the design department and workshop, relating to numerous grass-roots staff in an enterprise. To record each production process truthfully and accurately is an important guarantee for the quality of system operation in that various reports and statements in the system originate from these data collection, which is not only an important basis for enterprise manager’s decision-making, but also can be compared with different programming results of previous
prediction models, thus helping system implementation personnel improve and perfect the system. Therefore it is also the basis for the realization of information-based system.

On the other hand, mold production boasts unique characteristics, through which it requires large amount of workload after completing spare parts processing and assembling. It would be the key of obtaining quality product to design standard working process and various control report for the system.

The work procedure execution will involve numerous data, so the operation speed shall be considered when designing the system. Required work procedure data may be selected according to different combination, main parameters involved during the execution of work procedure shall include the follows:

1) Work number: the number of the worker responsible for the current production procedure, it is the mark identifying staff. One work procedure may be completed by several staff;

2) Apparatus number: there shall be one and only one apparatus for completing one work procedure. In case of two apparatuses required for one work procedure, then it shall be divided into two work procedures; virtual apparatus may be defined in case the actual apparatus is not definite. For example, virtual locksmith apparatus, virtual polishing apparatus and computer etc;

3) Products number (mold number): it is the identification mark of mould, which may be omitted if material number includes the mold number;

4) Material number: it is the identification mark for the piece under processing. Many work procedures may be processed by one work procedure. For example, several electrodes may be processed on CNC digital control machine tool. Work procedure for spare parts shall require the material number of the processing object, while some work procedures are not targeted at special spare parts, such as drawing of mold assembly drawing, locksmith assembly and mold commission program etc.

5) Status: it reflects the work status of current procedure, which would normally include:
   NW: new procedure not executed;
   OP: procedure under execution currently;
   PS: suspended procedure during execution;
   CL: completed procedure.

6) Start time and termination time: it can be used to select procedure to be started within certain time range.

7) Department: it can be used to select the procedure for department.

The said parameters can be combined in a random manner, for example, as shown in Fig. 4-51, the mold selected with the product number as LEH018406 was established during 2006/6/1 and 2006/7/18, and all work procedures were completed. The total work time (actual work time of the procedure series) was 1,406.98hr., while the ineffective work time is zero hour.

After inputting his own number and code, they may select the new procedure with the status as NW, and then change the new procedure into operation status OP by the ON button. In addition, the suspension/ resumption button of procedure shall be set to record the PS suspension and OP resumption status during the procedure operation. Such as the processing procedure of common machine, operator will suspend the procedure while coming off work and resume the same when going to work next time. When the procedure is finally completed, operator may press the Completion button to end the current procedure, and the completed procedure would be in the status of CL. Then, a procedure can be divided into several steps during its execution by PS action.
One procedure at least contains one work-step. The relation between procedure and work-step is:

- Procedure work hour = total work-step work hour
- Work-step work hour = actual completion time of work-step – actual start time of work-step
- Actual start time of procedure = MIN (Actual start time of work-step)
- Actual completion time of procedure = MAX (Actual completion time of wor-step)

The above operation is carried out when CAPP has planned the mold procedure. However, due to the complexity of mold processing, current auto CAPP normally has the accuracy of around 70%, in which there must be many redundant procedures. After the starting of mold commissioning procedure, the system will automatically search any new procedure not started, deem it as the redundant procedure and automatically delete it.

![Fig. 4-51: work procedure screening](image)

On the other hand, procedures not automatically set up by CAPP may be added by process staff or added provisionally by operator. For example, select a facility not in working status. After that, the system will deem that the current staff is the sole operator and require inputting product number and material number etc, setting up and initiating a new procedure.

In one word, the work input actually is an unplanned procedure operation. After inputting his own number and code, staff may directly select respective equipment and operate the start, suspension/resumption and termination of procedure.

To facilitate the system operation by workshop workers, the bar code input system similar with the above function may be introduced. However, the product number and material number may be prepared in drawings. Though the introduction of bar code may facilitate the input of operator, yet it may increase the preparation workload as well.