MICROMILLING TECHNOLOGY: Global review

Courtesy of the Doctoral Thesis of Endika Gandarias:
“MICROM: A revolutionary monitoring system to detect tool breakages & collisions, enhance machine cycles and introduce a new probing concept in micromilling”.

[Micro Manufacturing]
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MICROMILLING TECHNOLOGY: Global review

Micro-cutting machining has emerged recently as a vital aspect in meeting the requirements of technological advancement. The continuing quest for smaller, more reliable consumer and industrial products is pushing current limits in miniaturization technology [1].

1. INTRODUCTION

Micromilling is one of the emerging fabrication technologies. It is characterized by mechanical interaction of a sharp tool with the workpiece material, causing breakage inside the material along defined paths, and eventually leading to removal of the useless part of the workpiece in the form of chips [2].

Even though it may not be capable of obtaining as small feature sizes as in lithographic processes, it is important in order to bridge the macro domain and the nano/micro domains for making functional components [3-4]. There exists a wide variety of important applications in the commercial and defense sectors (e.g. masks for deep X-ray lithography [5], asymmetric high precision moulds [6], etc.), which require high-strength materials and complex geometries that cannot be produced using current MEMS fabrication technologies. Micromilling has the potential to fill this void in MEMS technology by adding the capability of free form machining of complex 3D shapes from a wide variety and combination of traditional and well-understood engineering materials (alloys, composites, polymers, glasses and ceramics).

In view of this, the fabrication of micro and meso-scale devices has presented researchers with new and exciting challenges.

This chapter realises a global review of the micromilling technology. First, the origin of the micromilling technology is described. Second, the micromilling machine is studied paying special attention to the elements that differ from macro machines, such as the machine bed, spindle, guides, driving systems and control & monitoring systems. Third, most commonly used microtool types and their weaknesses are described. Fourth, workpiece materials are described. Fifth, currently existing micromilling application areas are mentioned and some samples are depicted. Sixth, major cutting process differences between macro and micro world are studied. Finally, future micromilling challenges are described.

2. HISTORICAL BACKGROUND

Although wood-working machines have been in use since Biblical times, it was not until the late 17th Century that clockmakers, builders of scientific instruments, and furniture and gun makers began the changeover to machines capable of manufacturing steel. They had a need for a variety of gear cutting, grinding and precise screw-cutting machines to fabricate their products [7].
The first practical metalworking lathe was invented in 1800 by Henry Maudslay. It was simply a machine tool that held the piece of material being worked (workpiece) in a clamp (spindle), and rotated it so that a cutting tool could machine the surface to the desired contour. The cutting tool was manipulated by the operator through the use of cranks and handwheels.

Not much later, in 1818, American Eli Whitney built a pioneering horizontal milling machine; and in 1861, the American firm of Brown & Sharpe constructed the first truly universal milling machine, specifically for machining the grooves in twist drills (see Fig. 3.1).

Between the 1860s and the 1960s, there was an extraordinary quantum leap in humanity's capacity to transform raw metal into highly complex components. Together with contemporary developments in chemistry and electrical technology, this revolution in metalworking formed the industrial backbone of the modern world [10].

Brown's machine had set the stage for the developments of the twentieth century that were to follow; greater strength and rigidity, faster cutting speeds, higher precision, the inclusion of the electric motor and fully automatic operation [11]. These automatic aids to proficiency, always adhering to the double principle of accuracy and productivity, have increased through the years.

Based on these inventions, watchmaker and jewellers built milling machines capable of producing reliable and consistently small precision parts for serial production. New design and forms of components unimaginable until then at smaller sizes within tighter tolerances became possible for manufacturing. These initial steps established the origins of the forthcoming micromilling technology.

In 1983, Norio Taniguchi of Tokyo Science University illustrated the evolution that machine accuracy capabilities had underwent since the early 20th century, and the predicted the trend of these technologies for the following 30 years (see Fig. 3.2). Taniguchi would first define the concept of Nanotechnology to refer to the production technology to get the extra-high accuracy and ultra-fine dimensions [12].
3. MICROMILLING MACHINES

Size and quality of the micro-products depend on the properties of the used machine tools to manufacture them, including the overall accuracy and dynamic performance. Excellent capabilities of the machine tool are vital to such product requirements as size, accuracy, surface roughness and dimensional repeatability. In particular, machine bed, spindle, guides and driving systems result in key factors in the design of a micromilling machine.

Table 3.1 gives a rough approximation to the generic micromilling machine error sources.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>0.025µm at 15Krpm</th>
<th>0.050µm at 60Krpm</th>
<th>&gt; 1 µm beyond 100 Krpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle run-out</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle stiffness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool mount offset</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool geometry offset</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Axis accuracy (per axis)</td>
<td>Precision machining</td>
<td>&gt; 2 µm</td>
<td>FIB</td>
</tr>
<tr>
<td>Rotational Axis run out (per axis)</td>
<td>Highly Precise Systems</td>
<td>0.15 µm</td>
<td>Industrial Systems</td>
</tr>
<tr>
<td>Tool-tip deflection</td>
<td>&gt; 0.1 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool expansion *</td>
<td>&lt; 3-4 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece referencing</td>
<td>&gt; 1 µm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*This error is after CNC compensation. Tool expansion prior to compensation can be tenths of microns.

Table 3.1 Typical milling machine error sources.
Examples of some commercially available precision micромachining centres are depicted in Fig. 3.3a-b-c.

### 3.1. Machine bed & Architecture

Micromilling machine bed needs to damp outside and process generated vibrations, minimize the influence of changes in temperature, and guarantee a certain degree of stiffness [20].

Granite is preferred as the structural material due to the low coefficient of thermal expansion. Polymer concrete is also chosen in some cases, primarily due to the high damping characteristic. For increasing rigidity steel frames can be incorporated [17], and even alumina ceramic base structure prototypes have been studied [18].

Conventional milling machines can be found with a wide variety of configurations, as are dependent upon workpiece and process constraints (see Fig. 3.4).

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**Fig. 3.3** Commercial ultra precision machine tools: (a) Kern EVO [14]; (b) Kugler Microgantry GU [15]; (c) Fanuc ROBOnano [16].

**Fig. 3.4** Most common 3-axis milling machine configurations.
Most of the currently available micromilling machine architectures correspond to the vertical configuration, for which the vertical direction axis is at the tool side and the workpiece only has the horizontal degrees of freedom. This configuration is usually made use of in micromilling machines since gravity results not so critical resulting in lower risks to fall the components and reduced features distortions.

It is frequent in micromilling machines, as having an additional option, the possibility to implement a 4th and 5th axis on the basis of the three-axis vertical machining centre.

Process integration seems a usual feature in manufacturing of microproducts. Indeed, some commercial machines perform more than one machining process besides milling, such as, turning, grinding or laser.

### 3.2. Spindle

In micromilling, high revolution speeds are demanded due to the small tool diameters, and speeds as high as 250000 rpm are currently available. Nevertheless, it is generally agreed that spindle speeds must still considerably increase in the near future and cover a broader range of revolutions to achieve a competitive degree of efficiency compared with other micromachining processes. Currently used spindles make it frequently impossible to reach the recommended cutting speeds, even after using air turbine mechanism spindles. Indeed, considerable ongoing research to improve spindle capabilities is being carried out [19].

According to the high revolution and reduced thermal expansion requirements, ceramic bearing spindles or aerostatic spindles are mostly extended.

The spindle run-out and lengthening are other limitations which should be minimized since they influence the machinable tolerances and possible tool failures. The former can be originated due to the spindle error motion, tool clamping system or tool inherent geometrical errors while the latter requires a dimensioned cooling system to keep the temperature constant at very small intervals and minimize the spindle lengthening. The use of laser measuring systems is recommended in order to measure and take into consideration these enlargements (may reach values of 35 μm) [20].

In Table 3.2 the characteristics of some current commercial high-precision high-speed spindles are shown:

<table>
<thead>
<tr>
<th>Spindle Manufacturer</th>
<th>Type</th>
<th>Body diameter (mm)</th>
<th>Weight (kg)</th>
<th>Max. Speed (rpm)</th>
<th>Stiffness Radial (kg/μm)</th>
<th>Stiffness Axial (kg/μm)</th>
<th>Run-out (μm)</th>
<th>Static</th>
<th>Dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microdyne™ Air bearing</td>
<td>61.91</td>
<td>3.24</td>
<td>125K</td>
<td>0.59</td>
<td>1.07</td>
<td>5.00</td>
<td>8.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airturbine Tools 602JS  Ceramic bearings</td>
<td>39.67</td>
<td>0.68</td>
<td>90K</td>
<td>5.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Westwind D1733 Air bearing</td>
<td>53.34</td>
<td>1.86</td>
<td>250K</td>
<td>5.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precise SC 1060-OA Oil-air lubricated Hybrid ceramic</td>
<td>60.00</td>
<td>2.50</td>
<td>160K</td>
<td>2.50</td>
<td>1.70</td>
<td>2.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colibri Spindles HF80L2S140 Air bearing</td>
<td>80.00</td>
<td>9.00</td>
<td>140K</td>
<td>0.30</td>
<td>0.40</td>
<td>0.20 - 0.50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.2* Characteristics from the main high-spindle suppliers [21], [22], [23], [24], [25].
3.3. **Guides**

Fabrication of microstructures with micron details features and high accuracies is submitted to an ultra-precision stage (i.e. XY table). In order to maintain constant process conditions even at these details, the axes need to have a high acceleration as well as a stiff bearing to compensate process forces.

Next, most common types of bearings used in micromilling machine stages are compared; these include air bearings, hydrostatic bearings and roller bearings (see Table 3.3).

Hydrostatic guides are currently the most common systems for linear guides in high-precision micromilling machines. However, the use of aerostatic guides is increasing since it offers the highest resolution and great machine consistency due to zero wear. [16].

3.4. **Driving systems**

Another issue is the different kind of driving systems that are used in current ultraprecision machines. Depending on the degree of accuracy, single or dual actuator driving systems are found (see Fig. 3.5). Single actuators are friction drives, ball screws or linear motors, while dual actuators couple two driving systems, a coarse one such as a ball screw or a linear motor and a fine one such as a piezoactuator (PZT) or a voice coil motor (VCM).

![Resolution of different driving systems vs. working range](image-url)

**Fig. 3.5 Resolution of different driving systems vs. working range** [27].
Most commercial micromilling machines use single actuators driving systems. Ball screw drives provide lower accuracy compared with other options but, still reasonable resolution and accuracy. Linear motors provide backlash-free, friction-free motion and higher accelerations, so the attainable resolution is higher compared with ball screws driving systems [28]. Friction drives allow very high resolution, about 1nm, although they have low rigidity, low damping and low load capacity, which overall worsens the dynamic capacity.

So far, the most suitable equipment is linear drive motor with hydrostatic bearings. The positioning accuracy at high precision machining tools can be located at 0.15 μm per axis and around ± 2 μm at the workpiece [29].

3.5. Workpiece clamping and fixturing devices

The large variety of workpiece materials, geometries, and dimensions applied in micromilling demand the use of different type of clamping and fixturing devices as there is no unique standardised technique.

Clamping and fixturing devices need to fulfill requirements such as no deformation and contamination of components, fast workpiece exchange, high reproducibility and accuracy, stiff assembly, etc.

Furthermore, other factors such as, workpiece properties (strength, stiffness, chemical resistance, temperature resistance, magnetization susceptibility), workpiece dimensions and geometries, manufacturing forces, lot sizes, etc., need to be considered for an adequate selection of a clamping or fixturing method.

According to the way that the clamping and fixturing devices transfer the forces between the workpiece and the mount, they can be classified as follows (see Fig. 3.6):

- Force closure devices: bench vice, brackets, magnetic disk, vacuum clamping, etc.
- Form closure devices: screw fastening, self-centering clamping systems, etc.

![Fig. 3.6 Clamping and fixturing devices](image)

(a) brackets [30]; (b) magnetic chuck [31]; (c) vacuum chuck [32], (d) self-centering chuck/pallet systems [33]; (e) Gluing lines for workpiece fixturing [34]; (f) freezing mounts [32].
• Adhesive bond techniques: Gluing, embedding in metal or wax, freezing, magnetorheologic bonding, etc.

Lately, the self-centering chuck/pallet systems are the most extended methods as they allow the production of small series and transfer the workpiece from the machine to a separate measuring station and back, with high position reproducibility.

### 3.6. **CAD/CAM software**

The use of CAD/CAM systems in micromilling operations is widely extended to machine the small and complex workpiece geometries. However, currently available CAD/CAM systems do not present an adequate behaviour for micromilling process characteristics and specific CAD/CAM modules are required (see Fig. 3.7).

To adequately support the micro-milling process, the CAD / CAM software should be able to [35]:

- Accurately utilise the highly detailed mathematical model, while maintaining its level of complexity. Having an integrated CAD/CAM solution is ideal, since it eliminates any data translations in the process;
- Include high-accuracy, built-in CAD capabilities within the CAD system that can provide assisting geometry (e.g. capping, extending surfaces, etc.) with the appropriate accuracy and tangency within the CAM system;
- Support tool path calculation with tolerances down to 0.1 micron. This is especially challenging when machining miniature details in large size parts;
- Support calculation with micro-milling level parameters considering the constraints of the physical machines. For instance, the CAM system may be required to provide super-finish results with a tool diameter of 0.1mm, a side step of 0.005mm and a 10 times large round corner radius of 0.05mm. Tool paths must be created accurate to the fifth decimal point;
- Support machining strategies optimised for micro-milling, such as the machining of rough, re-rough and finish in the same NC operation;
- Use the knowledge of actual remaining stock throughout the entire process to adjust feed to actual tool load in order to lower machining time while protecting the delicate tools from breaking.

*Fig. 3.7 Commercial Cimatron CAD/CAM solution for micromilling: (a) CAD/CAM software image; (b) obtained final part [36].*
3.7. Control & Monitoring systems

Improved machining productivity, higher workpiece accuracies, and longer tool lives demand the implementation of precise and reliable control and monitoring systems.

Regarding the positioning systems, most commercial machines use glass scales (optical encoders) as it is the lowest cost option with a sufficiently high accuracy. A relatively good feedback control performance can be achieved when using hydrostatic and ball screws. Laser systems, on the other hand, show a higher positioning resolution although they are sensitive to environmental influences and make the machines considerably more expensive. Table 3.4 shows several types of positioning sensors available in the market.

Besides positioning systems control, there is a wide range of control systems to achieve better machining accuracy and longer tool life. Tool control is a primary concern, and so micromilling machine manufacturers have developed various systems to detect and measure the tool during machining. In that context, commercial products for control of specific features have emerged due to the demand of high precision at high spindle speeds. Examples of these control systems are contact probes and non-contact laser systems. However, further developments are required in this field, and chapter 4 analyses this area more extensively.

Thermal control, for instance, is another recently used control system which is increasing its acceptance amongst micromilling machine manufacturers. Currently, the highest precision machines, such as, the Fanuc Robonano or Cranfield Nanocentre provide a thermal control of the air and fluid systems in a very narrow range of about 0.01°C. Furthermore, the Tokyo Institute of Technology has recently developed a novel temperature control system of the spindle supply air with excellent results, which consists of cooling the input air while machining (see Fig. 3.8).

Table 3.4 Most common position sensor characteristics.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Resolution</th>
<th>Bandwidth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive sensors</td>
<td>0.1nm</td>
<td>10 kHz</td>
<td>Short measurement range.</td>
</tr>
<tr>
<td>Laser interferometer</td>
<td>&lt;1nm</td>
<td></td>
<td>Sub-nanometre resolution. Measurement is independent of stage motion. Expensive and complicated implementation.</td>
</tr>
<tr>
<td>Optical encoders</td>
<td>&gt;1nm</td>
<td></td>
<td>Resolution range (1-100nm). Less expensive and easy to implement.</td>
</tr>
<tr>
<td>Strain gauge</td>
<td>1nm</td>
<td>5 kHz</td>
<td>Very small, low heat generation.</td>
</tr>
<tr>
<td>LVDT</td>
<td>10nm</td>
<td>1 kHz</td>
<td>Good temperature stability. Bulky.</td>
</tr>
</tbody>
</table>

Fig. 3.8 Temperature control system: (a) supplied air temperature; (b) spindle temperature; (c) spindle displacement.
3.8. Small machines & Microfactories

Micromachine manufacturer trends present two clearly different conceptions worldwide; while Europe and most institutions and companies in U.S.A. are adapting current machines to the microtechnologies, Japan and some research centres in U.S.A. are developing tiny machines in order to reduce inertia and energy consumption, and to improve resolution.

Several researchers and companies are trying to scale down the machine tools to produce micro-components [37, 38, 39, 40, 41]. Micro-machine tools present several benefits from this miniaturisation including that of reduction in energy, space, materials and cost. Fig. 3.9 illustrates some miniature micro-machine tools.

The possibility to use more expensive materials that exhibit better engineering properties or lower thermal expansion due to a smaller construction, or higher natural frequencies of the micro-machine due to a smaller mass (regenerative chatter instability is shifted) are one of those benefits. In addition, smaller machine tools have lower vibration amplitudes [39].

The portability of such systems is beneficial, e.g. during military or space exploration applications. Microfactory is a concept that has been introduced recently referring to extreme miniaturization of a manufacturing system. Further, microfactories can have different cells with different functionalities such as micro-lathe, micro-milling and micro-press (Fig. 3.9c).

However, there are challenges associated with the development of small size micro-machine tools. Major development should be the increase in structural rigidity and reduction of the vibration influences. They require small enough accurate sensors as well as actuators to implant within the machines.

Fig. 3.9 Micro-machines: (a) miniature micro-lathe [42]; (b) miniature micro-extrusion machine [43]; (c) Microfactory [39]; (d) precision milling machine [44]; (e) 2nd generation 3-axis horizontal milling machine [45]; (f) 5-axis milling machine [38].
4. MICRO-CUTTING TOOLS IN MICROMILLING

Normally used microtool types for micromilling operations are end-mill, ball-nose, drills and engraving tools. These tools are usually made of tungsten carbide, and also of diamond material when not machining ferrous workpieces.

One of the main limiting factors for the miniaturization of the cutting process is the tool due to the reduced stiffness of the tiny sizes. Common tool wear in conventional milling cannot be used as an end tool life criterion in micromilling as premature tool failures occur frequently. Various authors [46-47] state that commonly observed tool breakages may be due to the following mechanisms:

- **Excessive stress-related breakage**: It will occur very quickly if the cutting force increases beyond the strength of the tool. The cutting force might increase for the following two reasons: first, the cutting edge might lose its sharpness or the cutting edge is partially damaged. And second, deposition of chips fills the microtools tiny grooves producing chip clogging. High Speed Steel (HSS) tools tolerate such chip clogging better than carbide tools since they are less rigid. However, it is almost impossible to predict chip clogging ahead of time. The workpiece starts to push the shaft of the tool and it deflects, increasing the static component of the feed direction force [46];

- **Fatigue-related breakage**: It may happen if the cutting force and the stress increase as a result of tool wear, and then stay at that level for an extended period of time. The stress on the shaft will change repeatedly while it is rotating [46];

- **Increase in the specific energy**: Tool failures occur due to the substantial increase in the specific energy required as the chip thickness decreases. This means that in the case of micromachining, as the chip gets thinner with smaller depths of cut, the microtool tip will be subject to greater resistance when compared with conventional machining [47].

Furthermore, tool run-out is another remarkable problem since it creates drastic changes in the cutting force profile. Tool run-out is caused by a misalignment of the axis of symmetry between the tool and the tool holder or spindle [48]. Due to that, it is quite common to see that only one cutting edge of a two-flute micro end mill performs the machining operations involving an increase in the force variation, and as a consequence, the tool wears out faster raising the tool failure probability [49] (see Fig. 3.10).

![Cutting force in micromilling](image)

**Fig. 3.10** Tool run-out effect, one cutting edge cut deeper than the other [50].
This run-out may create drastic force variations in the cutting forces since some cutting edges of the microtool perform more than the others during the machining operations.

Various partially conflictive requirements need to be met with in order to produce precision components. Depending on the required surface properties and workpiece material cemented carbide tools (CW) or diamond cutting tools are used (scarcely high-speed steel tools). Traditionally, diamond cutting tools have been used for ultra-precision machining operations, but because of the high demand for machining ferrous materials [51], carbide tools are considered better suited to achieve these ends.

4.1. Cemented carbide tools

Tungsten carbide cutting tools are generally used for the micro-mechanical cutting process due to their hardness over a broad range of temperatures and materials (see Fig. 3.11a-b).

Achievable surface roughness ranges between Rz 0.1-0.3 μm depending on the workpiece material [20] and other parameters. These tools are commercially available in diameters as small as 5 μm produced by grinding machining [52].

However, tool diameters below 100 μm are not fully reliable, thereby originating an unpredictable tool failure. Furthermore, microtools of diameter less than 50 μm need a zero helix angle to improve their rigidity [3, 53] and to mitigate the limitations of fabrication techniques. Some attempts have been done on it, e.g. ultrasonic vibration grinding to produce 11 μm diameter tool carbide [54], fabrication of a 25 μm diameter tool carbide using focused ion beam machining [55] or analysis of different geometries of microtools (triangular and D-shape bases) [56] (see Fig. 3.12).

In addition, wear reducing PVD-coatings (TiAlN, TiN, etc.) appear essential for dropping mechanical, chemical & thermal influences to obtain an economically reasonable tool life. The formation of droplets is still a major problem and needs to be addressed since the chip flow is complicated resulting in enlarged cutting forces and thus, a higher probability of tool rupture [20].

![Fig. 3.11 Cemented tools; (a) Hardness of cutting tool materials as a function of temperature [57]; (b) Scanning electron micrograph of Al 6061 machined at a feed rate of 10 mm/minute [3].](image-url)
4.2. Diamond tools

Diamond cutting tools present the capability to produce a surface roughness Ra in the range of 10 nm with an almost atomic sharpness of the cutting edge [59]. These tools are available down to sizes of 0.1 mm in diameter. However, diamond cutting tools are restricted to workpiece materials containing no ferrous elements due to the high affinity of iron to carbon. Above 700°C, diamond degenerates to graphite leading to devastating wear and final tool breakage.

Approaches for this problem are the reduction of the contact time between tool-workpiece by Elliptical Vibration Cutting [60], application of a nitrating coating [61], or use of other cutting tool materials such as cemented carbide, ceramics or different monocrystalline materials [62].

Recently, nanocrystalline diamond coatings on tungsten carbide micro-end-mills have been investigated with excellent results as an alternative to diamond tools [63].

5. WORKPIECE MATERIALS IN MICROMILLING

The machinable spectrum of materials by micromilling is broad (metals, polymers or ceramics) but yet, considering steels, limited to a certain hardness of around 50-55 HRC for commercially available microtools mainly due to the tools reduced stiffness. When cutting with diamond tools, another restriction for an economical process is that till date, the workpiece is nonferrous [20].

The micro-cutting of steel has recently received strong research interest with the initiation of miniaturised systems using a variety of materials, especially for biomedical applications and injection moulds. The most commonly used tool steel is 1.2343 (X38 CrMo V5-1), which can be hardened to 54 HRC.

Chemical reactivity with the cutting tool, crystal structures, defect distribution, and heat treatment are some factors that could affect the micro-machinability. It should also be considered that the material combined with the geometry of the part ought to be rigid enough in order to present a minimum distortion when clamping.

The assumption of homogeneity in workpiece material properties is no longer valid because micrograin size is often of the same order of magnitude as the cutter radius of curvature [64].
6. MICROMILLING APPLICATIONS

Emerging miniaturization technologies are potential key technologies of the future that will bring about completely different ways people and machines interact with the physical world.

Micromilling technology can meet many of those demands of miniaturised components in fields that include aerospace, automotive, biomedical, electronics, information technology, optics, telecommunication industries, jewellery, watch-making, etc.

Thus, many companies involving a broad field of areas, use micromilling technology integrated in their production systems [14]. Some companies are listed as example; Bic, Gillette, Bosch, Cerametal, Iscar, Sandvik Coromant, Seco, Rolex, Bauer Christian, Angiomed, Biacore, Curasan, Microtronic, Oticon, Phonak AG, Microparts Steag, Acritec, Alcon, Bausch & Lomb, Carrera, Arilens, Medicontur, Morcher, Star Surgical, Braun, Festo, GKN Sinter Metals, Esser, Amic, Daimler Chrysler, EADS, Fraunhofer Institute, Philips Research, Pro-micron, Siemens VDO Automotive, Daimler Chrysler, EADS, Philips Research, Pro-micron, Siemens VDO Automotive, 3M Unitek, Degussa, Ivoclar vivadent, Metalor dental, Dedienne, Feinmetal, IBM, Lumberg, Tyco electronics, etc.

Many shortcomings of photolithographic batch-processing techniques can be overcome using micromilling machining. Direct fabrication of masks for X-ray lithography by mechanical micromilling is an avenue for manufacturing cost-effectively low-volume production and prototypes [65].

In addition, the implementation of replication techniques, like microinjection moulding or hot embossing, rely on the availability of tooling technologies for manufacturing of tools and moulds. The mould and die industry in Europe has more than 5,500 companies and total sales of 10,000 M€ making an important industry [66].

It needs to be considered that micromilling is a rather incipient process in micromachining. Currently, few applications are clearly identified for micromilling such as X-ray mask making, mould making for micro-replication techniques, electrode making for electro discharge machining processes or watch making.

However, it is expected that micromilling components and applications will undergo an exponential growth in the following years [67].

Next, common micromilling applications are classified by field and then, real components are illustrated as shown in Fig. 3.13, Fig. 3.14 and Fig. 3.15.

- **Biomedical**: Microtools for surgery, moulds for medical components (microdosage systems), lab-on-chip, moulds for orthodontics (dental brackets), moulds for biotechnology applications (microchip electrophoresis devices, polymeric BIOMEMS devices, accelerating polymerase chain reaction for modular lab-on-a-chip systems), cataract lenses, retinal micro-tacks, etc.

- **Watchmaker and jewellery**: manufacturing and engraving of watch base plates, moulds for rings and pendants, etc.

- **Information technology**: Test membrane for PC chip manufacturing, etc.
- **Telecommunications**: mould for easy-assembly multi fibre connector for single and multimode applications, joining elements, etc.

- **Automotive**: Injection nozzles, electrodes for cutting inserts, etc.

- **Aerospace**: Miniature devices for rockets, mould for miniature planetary gear wheels attached to a turbine, etc.

- **Others**: Components for measuring devices, electrodes for toy industry, electrodes for manufacturing shaving head of electric razors, etc.

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**Fig. 3.13** Micromilling applications: (a) Lab-on-a-chip [68]; (b) Microplate with 96 capillarity electrophoresis system (vacuum hot-embossing plate from micromilled mould) and filling of one structure [69]; (c) Medicine microdosage system [70]; (d) Sweat-stick for collecting human sweat [71].
Fig. 3.14 Micromilling applications (continue): (e) Integrated polymer microfluidic stacks (chemiluminescence experiment); (f) Dental brackets [14]; (g) Tissue removal tools for endoscopy [14]; (h) Cataract lenses [14]; (i) Fabrication of Ti retinal microtack [72]; (j) Watch base plate [14]; (k) Engraving watch base plate [73]; (l) Watch parts [74]; (m) Pendant mould [75]; (n) Multi-fibre connector (micromilled mould for X-ray mask fabrication and micro-injected connector) [76]; (o) Joining element for optical fibre connector [14]; (p) Test membrane for computer chip manufacturing [14]; (q) Injection nozzles for diesel engines [14].
Fig. 3.15 Micromilling applications: (r) Electrodes for cutting inserts [14]; (s) Mixing disc of a rocket motor [14]; (t) Turbine wheels for microfluidic pumps [14]; (u) Assembled micro impeller and base block [38]; (v) Micromould of a planetary gear wheel [20]; (w) Small size plastic components [77]; (x) 24 cavity micromould with hot sprue [77]; (y) Electrode for manufacturing a toy locomotive [14]; (z) Electrode for manufacturing shaving head of electric razor [14]; (aa) Glass extrusion die for halogen lamp [14]; (ab) Setting screw for micrometer [14]; (ac) Modular mould insert tool for moulding housings for a hydraulically driven micromilling cutter [78]; (ad) Miniature microscope lens holder [79].
7. PROCESS CUTTING DIFFERENCES BETWEEN MACRO AND MICRO WORLD

Main principle of micromilling is similar to that of conventional cutting operations, in particular, the surface of the workpiece is mechanically removed using microtools. However, unlike conventional macro-machining processes, micromilling displays different characteristics due to its significant size reduction.

Next, major distinguishing factors between micro and macro milling are studied, such as, specific cutting energy, minimum chip thickness, surface roughness, burr, microstructure effect, tool wear, modeling, sensing and monitoring methods.

7.1. Specific cutting energy

Lucca et al. [80] noticed the specific cutting energy required to machine at very low chip-thickness values could not be explained by the energy required for shearing, and for overcoming friction on the rake face of the tool. The significance of ploughing and elastic recovery under these conditions was used to explain the increase in the cutting energy.

Lucca and Seo [81] observed the nominal rake angle and the tool edge profile had significant effects on the resulting forces and dissipated energy using single-crystal diamond tool edge geometry. When the uncut chip thickness approached the size of the edge radius, the effective rake angle determined the resulting forces (see Fig. 3.16a).

Lucca et al. [82] investigated the transition from a shearing dominated cutting process to a ploughing-dominated process in diamond turning by studying the angle of the resultant cutting forces in orthogonal cutting. They found that at uncut chip thickness values less than the edge radius, the force per unit width in the thrust direction increases more rapidly than the force per unit width in the cutting direction. The tool edge condition (tool wear) was found to have a significant effect on the thrust forces when the depth of cut was below the tool edge radius as shown in Fig. 3.16b.

![Fig. 3.16 Specific cutting energy: (a) Direction of resultant force vector for new and worn tools with the same overall tool geometry [81]; (b) Effect of tool edge condition on thrust force in orthogonal fly-cutting of Al 6061-T6 [82].](image-url)
Taminiau and Dautzenberg [83] also witnessed an increase in cutting energy while machining brass with decreased chip thickness. The authors discovered that the specific cutting forces depended only on the ratio of the uncut chip thickness to the cutting edge radius when the uncut chip thickness was smaller than the edge radius.

7.2. **Minimum chip thickness**

The minimum chip thickness \( (h_{\text{min}}) \) is defined as the minimum undeformed thickness of the chip removed from a work surface at a cutting edge under perfect performance of the metal-cutting system (no system deflection).

In macro-machining, the depth of cut is generally bigger than the cutting tool edge radius \( (\rho) \), and it is assumed that the cutting tools completely remove the surface of the workpiece and generate the chips [48].

However, in micro-machining, the small depth of cut compared to the edge radius of the tool (tungsten carbide tools \( \sim 1-2 \, \mu\text{m} \), diamond tools \( \sim 50\text{nm} \)) causes a large negative rake angle. The consequence of this is a process, which might be dominated more by rubbing and compression instead of by cutting [84]. This phenomenon causes a rough surface and elastic recovery of the workpiece, increasing the possibilities tool damages to occur (see Fig. 3.17) [1, 85-86].

Ikawa et al. [87-88] discussed the significance of the minimum thickness of a cut in diamond turning and it was found to be more strongly affected by the sharpness of the cutting edge than by tool-work interaction. The authors noted that the minimum thickness of cut might be of the order of 1/10 of the cutting edge radius.

The minimum chip thickness effect was also observed in the micromilling process. Weule et al. [89] were the first to point out the existence of the minimum chip thickness and its significant influence on the achievable surface roughness in micromilling. The authors hypothesized that the minimum chip thickness effect was responsible for the sawtoothlike surface profile (see Fig. 3.18). The minimum chip thickness to edge radius ratio for micromachining was estimated to be \( h_{\text{min}} = 0.293\rho \), which was much larger than that of nanometric cutting. They also noticed that the softer material state caused increased surface roughness and claimed that the minimum chip thickness was strongly dependent on material properties.

![Fig. 3.17 Cutting edge workpiece interaction in micromilling [53].](image-url)
Kim et al. [90] performed an experimental study to prove the existence of the minimum chip thickness in micromilling. It was found that for very small feed rates, the measured chip volume is much larger than the nominal chip volume, indicating that a chip is not formed with each pass of the cutting tooth (see Fig. 3.19a). Further evidence that a chip is not formed with each tooth pass is obtained by examining the distance between the feed marks on the machined surface. For a small feed per tooth, the distance between feed marks was found to be much larger than the feed per tooth, which also indicates that chips do not form with each pass of the tool. Thus, the tools had an oscillating movement, and the missing creation of a chip resulted in a deflection of the tool (see Fig. 3.19b).

Vogler et al. [91] experimentally studied the effects of minimum chip thickness on the cutting forces in micromilling. It was found when machining at small feed rates, the chip thickness accumulated and the force increased with each tool pass, for \( n \) tooth passes until the chip thickness was greater than the minimum chip thickness.

### 7.3. Surface roughness

Surface finish is very critical in micromilling as the machining operation is usually intended to produce components with high quality surfaces. Due to this, factors like vibrations, chip removal, etc. that are not so critical in the macro scale, have significant influence on the surfaces generated at the ultra-precision scale.

Vogler et al. [92] studied the surface generation in the micromilling process and it was found to be strongly affected by the tool edge radius and the feed rate. The authors observed that for the 2 µm edge radius, as the feed rate was reduced to a certain value, the surface roughness started to increase, indicating that an optimal
feed rate exists that will produce the smallest surface roughness value (see Fig. 3.20). The authors claimed that the existence of the optimal feedrate was due to the trade-off between the traditional effect of feed marks as the feed rate is increased and the minimum chip thickness effect resulting in tool passes that do not remove any material as the feed rate is reduced.

Lee [93] studied the effect of the feed rate, cutting speed and depth of cut on the surface roughness when machining aluminium. The author observed the effect of the cutting speed and depth of cut was by far smaller than the feed rate.

Furthermore, the surface roughness depends on the machining parameters used and the nature of the workpiece (e.g. grain size) and the tool condition; and it can be further improved by increasing the rigidity and accuracy of the equipment [94].

### 7.4. Burr

Burr is one of the major problems in micromilling. Burr cannot only harm people handling the machined parts, but it is also a problem in successive assembly processes (see Fig. 3.21).

Damazo et al. [95] reported that burr formation was a major limitation on the minimum wall size that could be machined (a 25.4 µm thick wall with a 305 µm height was successfully machined).

![Fig. 3.20 Effect of tool edge radius on surface roughness for pearlite [92].](image)

![Fig. 3.21 Two different kinds of burr: (a) exit burr; (b) top burr [96].](image)
In Lee and Dornfeld [84], experimental studies on micro-burr formation were performed in micromilling aluminium and copper. Different burr formation types were observed: flag-type, rollover-type, wavy-type and ragged-type (see Fig. 3.22). The burr on tool entrance and exit were found to be proportionally bigger than in conventional milling processes considering the ratio of burr size to chip load. The authors attributed this difference to the low cutting speed and large edge radius-to-chip load ratio in micromilling. In addition, the large tool edge radius-to-chip load ratio causes rubbing and compression instead of cutting and generates more burrs. The authors also noted that up-milling produced smaller top burrs than down-milling.

According to M.Xiao et al. [102], the burr is suspected to be influenced by the cutting edge radius and tool run-out, and be increased with increasing feed rate and depth of cut.

Litwinski et al. [97] studied the optimization of tool paths in order to minimize burr formation and avoid deburring processes from destroying delicate microfeatures.

In addition, deburring is very important because it cannot always be applied on miniature fabricated parts due to the possibility of damaging the workpiece [98]. Investigations have succeeded either in applying a removable coating onto the workpiece before machining (only suitable for soft materials) [53] or using electrochemical polishing.

### 7.5. Microstructure effect

In micromilling, a typical cutting depth of a few micrometers is common. With such a small depth of cut, chip formation takes place inside the individual grains of a polycrystalline material (usually between 100 nm and 100 µm) and hence, material microstructure effects will play an important role in micromachining.

Moriwaki et al. [99] found for single-crystal copper that the crystallographic orientation affects the chip formation process in terms of the magnitude of the shear angle and the cutting forces.
Fig. 3.23 Effects of the crystallographic orientation and the depth of cut on surface roughness [101].

Ueda and Iwata [100] observed on diamond cutting of β-brass a lamella structure on the free surface of the chip and reported the formation of discontinuous chips in a particular range of crystallographic orientations. The authors observed the cutting forces and surface roughness values depended on material anisotropy.

To et al. [101] conducted diamond turning of single-crystal aluminium and continuous chip formation was observed under all cutting conditions. They reported that for the {110} oriented crystals, the highest cutting forces and worst surface roughness were produced; whereas for the {111} oriented crystals, the lowest cutting forces; and for the {100}, the best surface finish were obtained (see Fig. 3.23). According to the authors, the surface roughness was substantially influenced by the crystallographic orientation, but not significantly affected by the depth of cut.

Vogler et al. [91] studied the effects of a multiphase microstructure on the micromilling cutting forces. The authors observed high-frequency energy components in ductile iron experiments but not in the single-phase ferrite and pearlite materials. This fact evidenced that these high-frequency components are due to the multiphase.

Vogler et al. [92] also investigated the effect of the multiphase material microstructure on the surface generation process. It was observed that multiphase microstructure materials had a worse surface roughness than single-phase material. The increased surface roughness was attributed to interrupted chip formation that occurs as the cutting edge moves between the multiple phases.

7.6. Tool wear

The small depth of cut in micromilling significantly increases friction between the tool and the workpiece, resulting in thermal growth and wear. As a result, the increased radius of the tool decreases the quality of the produced part and increases the rate at which tools fail [102-103]. Whereas tool wear monitoring has been extensively studied on the macro-scale, very limited successful work has been conducted at the micro-scale [104, 105, 106, 107, 108].

Tansel et al. [46, 104] have studied the effect of wear in the micromilling process. They have found that, unlike at conventional sizes, the tool does not gradually wear until it causes undesirable surface effects, but rather the tool breaks quickly as it becomes
The fracture of the microtools is due to the increased cutting forces with the dulling of the cutting edges causing the stresses to exceed the strength of the small diameter tools.

Miyaguchi et al. [23] found that tool wear in a micromilling process is partly responsible of the stiffness of a micro-end-mill tool. They concluded that because of the spring-back of an end mill under the thrust force, the effect of tool run-out is reduced and the abrasion of each tool edge tends to be uniform.

Rusnaldy et al. [109] investigated the tool wear mechanism and the factors that affect the tool wear analysing the vibration and cutting forces on machining performance. It was observed that the higher the machining time, the higher was the tool wear, although the cutting force and tool vibration were not affected by this increasing time.

### 7.7. Modeling

The aforementioned differences between micro and macro machining makes necessary the development of new models which take into account micromilling particularities. Furthermore, larger values of feed per tooth are demanded to improve machining productivity. These aggressive conditions lead to higher stresses on the microtools, and in consequence, more accurate prediction models are required [110].

Mostly used methods for the characterisation of microcutting phenomena include molecular dynamics (MD) simulation, the finite element method and mechanistic process modeling [1]. This latest method, the mechanistic process modeling, is the more extended one in micromilling.

MD simulation performs analysis at the atomic level based on the atomic interaction potential and is best suited for nanometric cutting.

The underlying theory in the finite element modeling of machining is macroscale continuum mechanics and it has been mostly used for investigating orthogonal microcutting [111-112].

The mechanistic modeling approach is directed towards deriving a model that combines a comprehensive characterization of the cutter and cut geometries to relate the process inputs to outputs with a small number of experiments.

Bao and Tansel developed a first model for micomilling process based on Tlusty’s model [113] that includes the effect of trochoidal nature of the tool path [110], the effect of tool run-out [114], and the effect of tool wear [115]. However, these models considered the workpiece material to be homogeneous.

Vogler et al. [91] developed a mechanistic model that used a mapping technique to represent the microstructure for heterogeneous materials (i.e. ductile iron) and determined the magnitude and variation of the cutting forces in micromilling (see Fig. 3.24). The model was shown to be capable of capturing the high frequency variation of the cutting forces that was observed in experiments when machining ductile iron. The simulation studies showed that the frequency of
the variation is attributed to the spacing of the secondary phase, and that the magnitude of the variation is determined by the size of the secondary phase particles.

Later, Vogler et al. [116] extended their previously developed micromilling force model in order to explicitly account for the cutting edge radius and were the first to incorporate the minimum chip thickness effect. The cutting forces originating from two mechanisms, chip removal and ploughing/rubbing were computed separately using slip-line plasticity and interference volume, respectively. It was noted that the predicted cutting force signal contained a repeated pattern for every \( n \) tooth passes, which provide an additional evidence of the minimum chip thickness phenomena in micromilling.

Based on their previous experimental studies [90], Kim et al. [117] developed a static model of chip formation in micromilling, which is able to describe the intermittency of the chip formation observed at low feed rates due to the dominance of the minimum chip thickness effect. The model was validated verifying the level of periodicity in the cutting forces present at various feed rates.

M. T. Zaman et al. [118] developed the first three-dimensional analytical cutting force model for micro-end-milling operations. This model established a new concept to estimate the cutting force in micro end milling by estimating the theoretical chip area instead of undeformed chip thickness.

C. Li et al. [119] developed an enhanced three-dimensional cutting force model for micro-scale end-milling by considering the combination of exact trochoidal trajectory of the tool tip, tool run-out and minimum chip thickness effect due to the intermittency of the chip formation at micro-scale.

X. Liu et al. [120] developed an analytical model to predict the minimum chip thickness values, which are critical for the process model development and process planning and optimization. The model accounted for the influence of cutting velocity and tool edge radius on the minimum chip thickness.

Vogler et al. [92] developed a process model for the prediction of the surface roughness for the slot floor centerline and cutting forces. The model explicitly accounted for the effect of finite edge radius by incorporating the minimum chip thickness concept. The model showed to accurately predict the surface roughness for single-phase materials, i.e. ferrite and pearlite.
X. Liu, M. B. G. Jun et al. [85, 121-122] developed a dynamic cutting force and vibration model of the micromilling process that accounts for the dynamics of the micro end-mill tool, influences of the stable built-up edge, and the effects of minimum chip thickness, elastic recovery, and the elastic-plastic nature in ploughing/rubbing. The authors studied the effects of the minimum chip thickness on the cutting forces and vibrations as well as the stability of the micromilling process. Concerning the forces, the rate of increase for both the cutting force and thrust force was found to be much higher for ploughing/rubbing (when the chip thickness is smaller than the minimum chip thickness) than for the chip formation process (when the chip thickness is larger than the minimum chip thickness). Further, a local maximum of the thrust force at the minimum chip thickness, due to the transition between ploughing and shearing was observed (see Fig. 3.25). The authors, unlike that of macro cutting processes, also noted that stability of the process was very sensitive to the feed rate.

A. Dhanorker and T. Özel [123] developed mechanistic and finite element models for micromilling to predict forces, stresses and temperature distributions in the presence of tool edge ploughing (see Fig. 3.26). Large force variations were observed as the diameter of the cutter decreases and the spindle speed increases. FEM modeling was found to be a promising method for simulation of chip flow and predictions for forces and temperature fields for meso end milling.
D. L. Wissmiller and F. E. Pfefferkorn [124] gave the initial steps to characterise the heat transfer in micro-end mill tools during machining operations. Experimental tests were realised measuring the tool temperature with an infrared camera and a finite element model (FEM) was developed for comparison. The results of the numerical model were quantitatively in good agreement with the measured temperature values for the steel cases, although they need to be improved for aluminium cases.

D. L. Wissmiller and F. E. Pfefferkorn [125] gave the initial steps to characterise the heat transfer in micro-end mill tools during machining operations. Experimental tests were realised by measuring the tool temperature with an infrared camera and a FEM model was developed for comparison. The results of the numerical model were quantitatively in good agreement with the measured temperature values for the steel cases, although they need to be improved for aluminium cases.

E. Uhlmann and K. Schauer [126] carried out a load analysis of current micro end mills using a FEM model for strain simulation, and an innovative parametric tool design of micro end mills was developed (see Fig. 3.27). This new design was successfully verified and a process-reliable increase in endurance of up to 30 % and an aspect ratio of 5:1 were achieved for a hardness of 62 HRC.

7.8. Sensing & monitoring methods

Proper sensing and monitoring of the micromilling process results in an essential demand for high accuracy components at micro scale-level that requires a thorough process control.

Significant research studies have been conducted on the monitoring of macro-machining processes using various sensors such as spindle motor current and power, vibration signatures, acoustic emissions, cutting forces, etc. However, a direct application of these sensing methods to the micromilling process is not feasible because of their narrow frequency bandwidths, low sensitivity to small disturbances, or simply their impossibility for milling operations due to the highly intermittent nature of the chip removal process.

Despite years of research in this area, reliable, versatile and practical sensors are not yet available for the monitoring and controlling of micromilling processes.

Chapter 4 focuses in detail on this topic, analysing current state-of-the-art of tool control monitoring systems and sensing methods for the micromilling process.
8. FUTURE CHALLENGES

Micromilling, as described previously, is an emerging fabrication technology with a promising future. It is envisaged as technology of choice to create complex three-dimensional shapes in hard engineering materials, especially for biomedical applications and injection moulds.

However, this requires addressing in the near future, the following challenges that are listed below:

- Increase the knowledge related to micromachining process parameters for materials different to silicon, e.g. steel, aluminium, ceramics, PMMA, etc., and in consequence, increase micromachined components applications;

- Improve microtools rigidity in order to reduce premature & unpredictable tool failures, achieve reliable tools on diameters below 100 μm, be able to machine harder materials (innovation regarding different types of coatings) and increase the removal rate [127];

- Investigate new techniques in diamond cutting process making it more compatible for the machining of ferrous materials, e.g. ultrasonic vibration, carbon rich gas chamber, cryogenically cooled chamber, etc.;

- Increase the rotational speed of the spindle to achieve recommended cutting speeds and cover a broad range of revolutions with minimum spindle run-out and lengthening;

- Reduce tool run-out and increase stage positioning precision since it creates drastic changes in the cutting force profile and excessive tolerances;

- Improve the structural rigidity and reduce the influence of vibrations of the microfactories;

- Develop specific models for micromilling, considering factors like minimum chip thickness, heterogeneity of the material, ploughing & elastic recovery and different materials;

- Develop specific CAD/CAM modules for micromilling processes with optimized milling strategies, tight machining tolerances and remaining “micro stocks” recognition;

- Research on reliable, versatile, economical and practical sensing methods for monitoring and controlling the micromilling process, in particular the employed microtools.
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