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To cite this article: Azfar Khalid *et al* 2022 *J. Micromech. Microeng.* **32** 063002

OPEN ACCESS
IOP Publishing

Journal of Micromechanics and Microengineering

J. Micromech. Microeng. **32** (2022) 063002 (21pp)

https://doi.org/10.1088/1361-6439/ac6b7d

Topical Review

Meso scale component manufacturing: a comparative analysis of non-lithography and lithography-based processes

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Received 23 August 2021, revised 19 February 2022
Accepted for publication 28 April 2022
Published 12 May 2022

Abstract

The paper identifies the meso scale (10 μm to few millimeters) component size that can be manufactured by using both lithography and non-lithography based approaches. Non-lithography based meso/micro manufacturing is gaining popularity to make micro 3D artifacts with various engineering materials. Being in the nascent stage, this technology looks promising for future micro manufacturing trends. Currently, lithography based micro manufacturing techniques are mature, and used for mass production of 2D, 2.5D features and products extending to 3D micro parts in some cases. In this paper, both the techniques at state-of-the-art level for meso/micro scale are explained first. The comparison is arranged based on examples and a criterion is set in terms of achievable accuracy, production rate, cost, size and form of artifacts and materials used. The analysis revealed a third combined approach where a mix of both techniques can work together for meso scale products. Critical issues affecting both the manufacturing approaches, to advance in terms of accuracy, process physics, materials, machines and product design are discussed. Process effectiveness guideline with respect to the component scale, materials, achievable tolerances, production rates and application is emerged, as a result of this exercise.

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Keywords: non-lithography, lithography, micro/meso scale manufacturing

(Some figures may appear in colour only in the online journal)

1. Introduction

The integration density of electronic devices has been increased for over three decades in combination with technological innovations and business outcome. Lithography based micro manufacturing (LBMM) has remained the mainstream production technique to meet such demand. From the last two decades, non-lithography based meso/micro manufacturing (NLBMM) which are primarily material removal technologies are progressing well and the concept of micro factories have emerged [1–3]. Initial efforts were made using macro scale machine tools with micro-nano machining modules reaching feature size and accuracies in sub-micrometer range [4]. In the recent years, the technology has grown to a maturity level as micro machine tool development became a popular research interest. Many research groups and companies have developed these desktop machines claiming submicron level accuracies, despite the technical challenges in terms of low static and dynamic characteristics and requirement of very high spindle speeds in order to improve material removal rates [5]. Meso/micro part manufacturing of complex 3D shapes is successfully pursued using NLBMM techniques [6]. Micromachining can be defined in many different ways depending on the industry, feature size, and focus of interest. This paper focuses first to sketch a clear line between NLBMM and LBMM processes for meso/micro scale applications. For example, NLBMM are primarily material removal processes by geometrically defined cutting edges for the purpose of creation of precise three dimensional work pieces with dimensions in the range of a few tens of nanometers to some few millimeters [7]. In this definition of machining, the typical material removal processes are cutting, polishing and abrasive using different tool engagement methods as NLBMM is defined as mechanical cutting of features with tool engagement of less than 1 mm with geometrically defined cutting edges.

NLBMM covers a broad range of fabrication techniques for small scale parts and these micro manufacturing processes are combined to contribute towards microproduct development. Ultra-precision micro manufacturing methods are mostly comprised of the electrolytic in-line dressing (ELID) to produce smooth and curved surfaces, electro-chemical machining (ECM), die sinking electro discharge machining (EDM), wire cut electro discharge machining (WEDM) and laser micro machining (LMM) are employed at the meso scale for hard to cut materials and prototyping [8–10]. On the contrary, traditional machining processes like milling, turning, grinding, polishing and lapping have their limitations up to the micron level. According to the Taniguchi Accuracy graph modified by McKeown [11, 12], the machining accuracy limits of NLBMM processes have achieved 1 nm using present day ultra-precision machines (UPMs) [13, 14].

Micro components achieved using LBMM have also shown a remarkable progress. The critical dimensions of the component devices and features has been decreased from 15 μm (first integrated circuit) to $\leqslant$45 nm [15], which is obtained by the next generation lithography (NGL). This is primarily considering two main factors: the feature size that is limited by the conventional optical mask process, and the cost which are expensive to operate, thus affecting the economy to make a reasonable profit through microelectronics industry. These processes generally include exposure, development, etching, sputtering, thermal removal processes, etc. Many of these chemical and thermal processes are used in the semiconductor industry and for micro-electro-mechanical-system (MEMS) related applications. This is referred as micromachining or LBMM with respect to this study and the feature size is considered $\geqslant$100 nm.

In LBMM, the basic feature size is defined by the wavelength of light used. Figure 1 shows the decrease in the exposure wavelength and the minimum feature size of large-scale integration (LSI) devices over the years. The line representing the device miniaturization trend is steeper than the rate at which exposure wavelengths have been reduced. The current status of minimum feature size is presented in figure 1 [16, 17]. LBMM as the workhorse of the microelectronic industry, is subjected to the enhancement of the resolution for the smallest feature size. Furthermore, the post optical lithographical techniques, commonly known as NGL techniques are also important for finished products. Although several other contact based patterning techniques have been demonstrated such as nano-imprint lithography [18, 19], a shift by the microelectronic industry from the contact based techniques to non-contact techniques, such as x-ray, e-beam direct write, extreme ultraviolet (EUV), electron projection lithography, ion projection lithography (IPL) and focused ion beam, require the introduction of new tools, materials and process engineering technologies and research and development (R&D) costs.

3D printing at meso range has become a state-of-the-art technology. For the advancement in micrometer-scale, few interesting techniques have already been evolved from laboratories and moving towards industries, for example, direct laser writing and multi-photon absorption printing. These technologies are extremely important for optical industry to achieve the reliable fabrication of multi-level micro lenses [20]. On the contrary, the existing printing speeds are extremely slow to yield reasonable throughput at nanometer-scale. However, focused ion- or electron-beam deposition techniques exhibit 3D nanofabrication capabilities whereas the highest resolution for 3D patterning solutions are currently available by Scanning Probe techniques [21].

The purpose of this review is twofold. First, the identification of both processes with regards to the products/applications and their features are highlighted including the

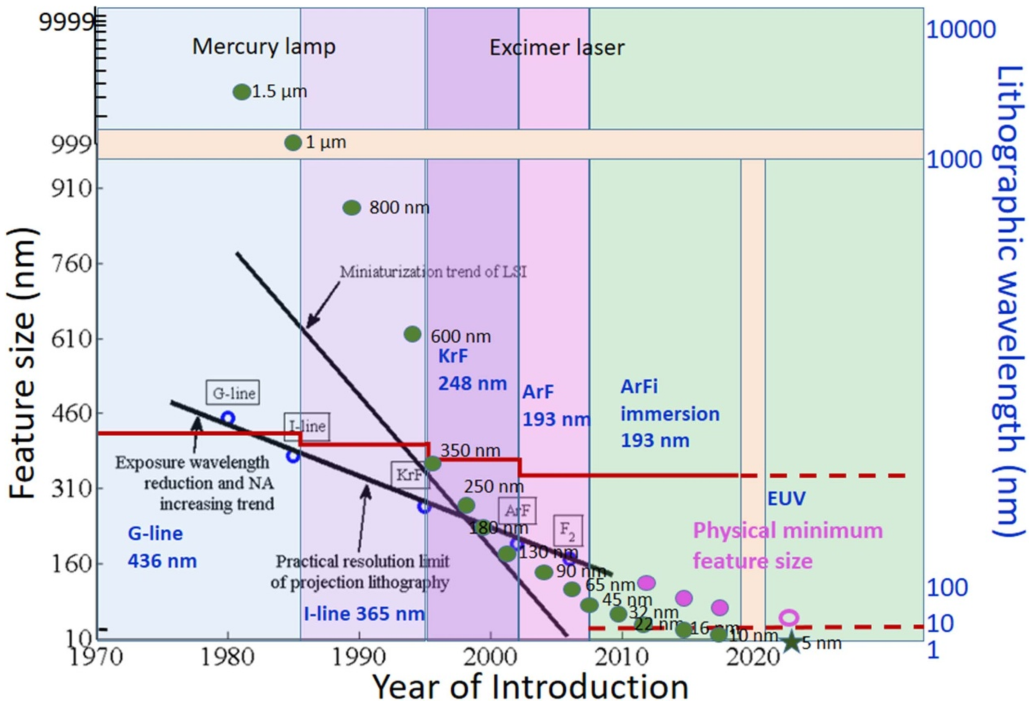


Figure 1. Comparison of the exposure wavelengths of various sources and the minimum feature size with timeline. Reprinted by permission from Springer Nature Customer Service Centre GmbH: [Springer Nature] [Nature] [16], (2000). Reproduced with permission from [17]. [Luong V 2018 Presentation EUV Lithography Coming to your local IC manufacturer! SoonTM, Arenberg, Youngster Seminar Leuven.]

third combined approach where the two techniques are merged as a process. Secondly, a comparison criterion is established in order to evaluate the application specific strengths and weaknesses of the two techniques followed by the future challenges that may influence the direction of development. As a result of comparison, a process effective guideline is developed that clearly highlights the application oriented LBMM and NLBMM characteristics.

2. Meso-scale manufacturing: an overview

Meso-scale manufacturing is reviewed using both techniques of LBMM and NLBMM. NLBMM largely involves the traditional manufacturing processes at meso scale that can form complex 3D geometries with a large variety in engineering materials. These processes are characterized by low to medium production rates, attainable high accuracies with miniature feature size and moderate level initial capital investment. The LBMM seems advantageous due to very high accuracies and production rates enabling the technology to keep the products cost low. However, LBMM needs large scale initial investment on fabrication facilities. Some details of the state-of-the-art manufacturing processes and the precision systems used for manufacturing of meso and micro scale components in both the approaches are given below.

2.1. Non-lithography based meso/micro scale manufacturing

NLBMM has variety of processes and machines at different scales. The list includes conventional processes like micro milling, turning and drilling as well as ELID, ECM, EDM, WEDM, abrasive micro machining, LMM and 3D printing at the meso scale. Traditional micro machining processes were initially conducted through large scale machines [22–24], but proved uneconomical in terms of bulk material removal, large energy and space usage. In order to improve process efficiency, the micro machines were built for comparable work piece size and features. Some representative processes are explained for state-of-the-art micro/meso scale applications in table 1.

2.1.1. Micro machining. In this paper, NLBMM using small size machines are taken as examples as these machines are at the cutting edge in terms of economical micro feature development. Such machines have superiority in commercial prototyping at meso scale. NLBMM with desktop and standard size machines are reviewed in [4], in which classification is highlighted on the basis of machine foot-print size and the accuracies attained. The best example in terms of micro machine specifications is of FANUC's 'Robonano'. Though the machine foot-print size is large to maintain the high stiffness level, but the model is developed for micro manufacturing. ROBONANO α-*0iB* is a five axis computer numerical control (CNC) precision μmachining center. It is a multi-purpose machine used for milling, turning, grinding and shaping with a linear axis resolution of 1 nm. FANUC series 30i controller is applied for the CNC. Static air bearings are selected for the movement of slides, feed screws and direct drive motors. The machine has an overall size of 1500/1380/1500 mm^3 and the stroke length of 280 $\times$ 150 mm^2 in the horizontal direction and 40 mm in the vertical direction.

Table 1. NLBMM representative processes at Meso-scale. Reproduced from [25]. CC BY 4.0. Reproduced from [26]. CC BY 4.0. This [File:Wire erosion.png] image has been obtained by the author(s) from the Wikimedia website where it was made available [LaurensvanLieshout] under a CC BY-SA 3.0 licence. It is included within this article on that basis. It is attributed to [LaurensvanLieshout]. This [File:Schematic representation of Fused Filament Fabrication 01.png] image has been obtained by the author(s) from the Wikimedia website where it was made available [KDS4444] under a CC BY-SA 4.0 licence. It is included within this article on that basis. It is attributed to [KDS4444]. Reproduced from [27]. CC BY 4.0.

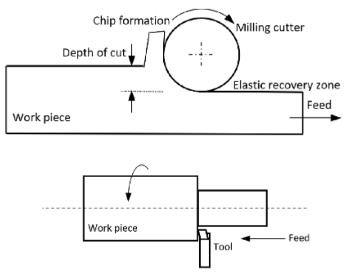
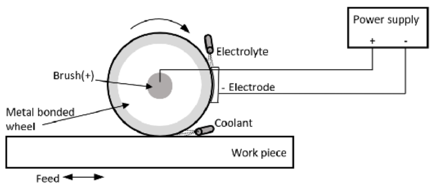
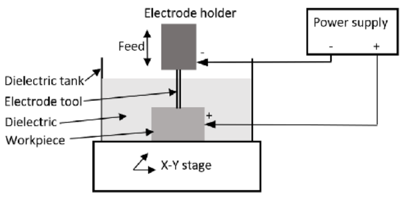
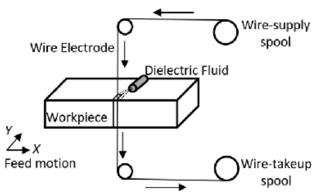
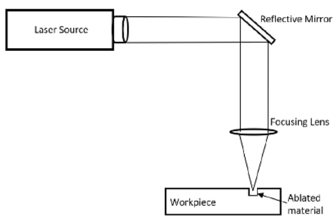
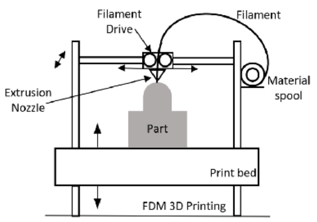
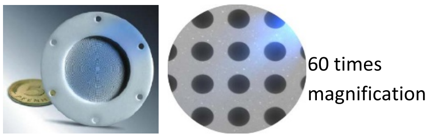
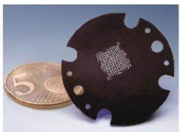
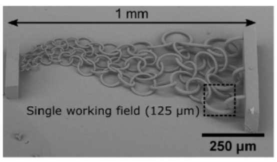
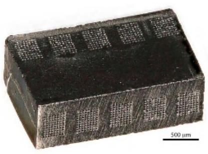
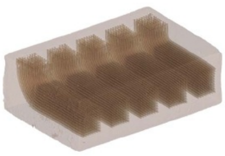
Sr. No.	NLBMM processes	Process physics: Process sketch	Process physics: Process for meso scale
1	μmilling/ μturning		Micro milling with standard size tools causes negative rake angle due to large tool edge size and small depth of cut and feed rate, resulting in rough surface of workpiece. Due to small workpiece size, distortions linked with residual and thermal stresses in workpiece remain significant [28]. Very large spindle speed is required to maintain the cutting speed, due to small tool diameter. Tool deflection in smaller tools is a significant problem [29]. In micro turning, workpiece loses rigidity and deflect due to thin cross-section. This can be minimized by reducing thrust force of the tool [30].
2	μELID		Electrolytic in-process dressing with metal bonded grinding wheels is used mostly for finishing optical surfaces, ceramics and metals. As brittle materials behave plastically at the nano meter scale, ductile-mode grinding is possible due to the formation of oxide layer on the grinding wheel surface. Uncut chip thickness is critical, as an increase in thickness can cause enough potential energy increase upon indentation to start cracking [25, 31].
3	μEDM		Micro EDM is suitable for efficient and burr-free, development of micro features, but the process is still not ideal for mass production. Small size tools and electrodes of less than 0.1 mm diameter are not available commercially. For very small electrodes, the tool wear significantly increases, when electric discharge capacities are slightly increased to enhance the process efficiency, but the micro feature quality is lowered. To maintain discharge energy, for micro EDM application, resistor capacity pulse generator is commonly used [26].
4	μWEDM		WEDM in the micro-meso scale is achieved, by use of thin copper wire of diameter of 50–250 μm, that is used as the moving electrode. Dielectric fluid helps to flush the melted and evaporated workpiece material after each electrical discharge event. It is important to install a precision motion system for wire guidance and wire tension must be kept high in order to avoid deviated surfaces, tapering and undesired edges [32–34].
5	LMM		Laser micromachining works with a laser source, reflecting and focusing optics. The most important factor is the timescale involved as continuous wave, short and ultrashort. Ablation occurs and the size of the heat affected zone is associated with the time scale and the beam diameter of the laser pulse. The biggest zone emerges in continuous wave laser. Ablation with femtosecond laser with a beam diameter of as low as 1 μm can give an accurate dimensional control for meso machining as compared to nanosecond and picosecond lasers [35, 36].
6	μ 3D printing		3D printing is an additive manufacturing technique that fabricates parts using four developed technology types namely stereolithography (SLA), powder bed fusion, fused deposition modeling (FDM) and inkjet printing. The earlier two methods use the laser, UV or electron beam source to initiate the resin reaction or material fusion. FDM use thermoplastic based continuous polymer filament that is heated at the nozzle stage and the extruded material sits on the previously printed layer. Use of these methods for micro-meso manufacturing is growing fast and the product quality is highly linked with the method employed, resolution, surface finish and layer bonding. Present day SLA can make micro features of size 10 μm with good accuracy and structural integrity [27, 37, 38].

Table 2. Meso scale artefacts using NLBMM techniques. Reproduced with permission from [39]. [KERN Microtechnik GmbH source]. Reproduced with permission from [40]. [© BMF Boston Micro Fabrication]. Reproduced from [41]. CC BY 4.0.

Sr. No.		Example	Process/material	Feature size	Machining time/ accuracy/ resolution
1	Test membrane for computer chip manufacturing (Courtesy of KERN Microtechnik GMBH) [39]		Drilling of large number of holes/Macor	Dia. 130 μm	7.8 s for each hole/$\pm$2 μm
2	Micro turbine wheel for high-speed micro fluidic pumps (Courtesy of KERN Microtechnik GMBH) [39]		five-axis machining/high performance polyimide based polymer (Vespel)	Dia. 0.7 mm	—
3	Test membrane for electronic chips manufacturing (Courtesy of KERN Microtechnik GMBH) [39]		Drilling of 648 holes from both sides/Vespel	Thickness: 0.5 mm Drill dia.: 60 μm	Total machining time <20 min/$\pm$2 μm
4	Medical device—Endoscope shell (Courtesy of Boston Micro Fabrication) [40]		Micro-precision 3D printing utilizing projection micro stereolithography	9.8 mm $\times$ 9.8 mm $\times$ 13.8 mm Tube diameter = 1.2 mm, min. wall thickness = 65 μm	Tolerance = $\pm$0.025 mm Resolution: 10 μm
5	1 mm long gradient chain-mail [41]. Smooth surface with features that range from μm to hundreds of μm		3D laser lithography or multiphoton stereo-lithography	Internal radius of the largest ring: 100 μm smallest ring radius: 5 μm	Total fabrication time: 26 min/Step size for slicing and hatching: 0.3 μm
6	3D Integrated microelectronic subsystems (Courtesy of Boston Micro Fabrication) [40]	 	Projection micro stereolithography (PμSL). Low-viscosity ceramic metallized to allow conductive connections.	Curved routing via hole diameter: 10 μm Pitch: 20 μm	Printing resolution: 2 μm
7	Hard milled mold insert (Courtesy of KERN Microtechnik GMBH) [39]		M340 mold steel Hardness: 56 HRC	Groove width: 0.2 mm Groove depth: 0.6 mm	Cycle time: 30 h Smallest end mill: Ball Ø 0.2

Surface roughness of Ra 1 nm is achieved in the turning operation on aspherical lens core of material Ni-P plate. Table 2 shows some meso scale manufacturing examples using materials like ceramics and metallic alloys for getting complex 3D shapes. These examples show the state-of-the-art NLBMM capabilities in terms of variety of shapes in 3D at meso scale. Some state-of-the-art micro machines and the specifications are shown in table 3.

Table 3 is showing the comparison of the capabilities and design aspects of current state of the art micro machines. There are machining centers, milling and turning machines and a hybrid machine capable of micro EDM, WEDM, ECM and ELID grinding. Micro milling and other machines made by the AIST, Japan are the smallest in size and weight. Robonano machining center has the highest resolution achieved as compared to other machines. Robonano has also achieved the

Table 3. Comparison of micro cutting machines (NLBMM): features and capabilities.

Machines	Make/overall size dimensions L × W × H (mm^3)	Designed for micro machining processes	Maximum spindle speed	Smallest work piece dimensions/accuracy achieved	Positioning accuracy/resolution
MTS5/MTS6 (Micro milling)	Nano Corporation, Japan [42]/260 × 324 × 370	Milling	20 000 rpm	50 × 50 × 16 mm^3/sub-micron surface roughness achieved	±1 μm/0.1 μm
Micro turning/milling	AIST, Japan [2] 32 × 25 × 30.5(Lathe)	Turning/surface cutting, drilling	10 000 rpm/ 20 000 rpm	Ø2 mm/4 × 4 mm^2 Surface roughness: 1.5 μm, Roundness: 2.5 μm	±0.5 μm/0.05 μm
ROBONANO *α-0iB*	FANUC, Japan [13] 1500 × 1380 × 1500 Travel X/Y/Z 280 × 150 × 40	Milling, turning, grinding and shaping	70 000 rpm	Surface roughness: R_a 1 nm is achieved while turning aspherical lens core	0.001 μm (resolution)
MMT—Micro	KERN Germany [39] 3110 × 1510 × 2965 Travel X/Y/Z 350 × 220 × 250	Milling, drilling	50 000 rpm	Ø350, H: 200 mm/ ±2.5 μm	±1 μm/0.1 μm
DT-110	Mikrotools, Singapore [43] 3000 × 2000 Travel X/Y/Z 200 × 100 × 100	Turning, milling, EDM, WEDM	5000 rpm	Silicon grinding: Surface roughness: R_a 3 nm	±1 μm/0.1 μm
AGIETRON MICRO NANO	Agiecharmilles, Switzerland [44] Travel X/Y/Z Micro module: 220 × 160 × 100 Nano module: 6 × 6 × 4	Die sinking EDM	—	Surface roughness Micro module: R_a 0.1 μm Nano module: R_a 0.05 μm	Micro module: ±1 μm/0.1 μm Nano module: ±0.1 μm/0.02 μm

highest work piece quality with a surface roughness of 1 nm. MMT from KERN, Germany and Robonano has the highest spindle rotation speeds reaching 70 000 rpm. MTS series from Nano corporation, Japan has developed many micro lathes and milling machines. The micro lathes are capable of machining submicron level circularities and work piece surface roughness. Micro machines shown in figure 2 are some state-of-the-art developments in the NLBMM cutting processes and major examples are developed by the commercial companies. Figure 2(d) is showing an example of a three-axis CNC micro machine using a nature inspired machine frame design for high structural stiffness with a conical egg-shaped cut in granite machine frame. A similar example is of KERN Pyramid Nano [45] where submicron accuracy is achieved through five serial axis attached with a pyramid structure and hydrostatic bearings.

2.1.2. Micro EDM. Other micro machining processes like ELID, ECM, EDM, WEDM, abrasive micro machining, LMM [46, 47] and micromolding can also be included for micro features development. DT-110 developed by Mikrotools, Singapore has capabilities of variety of ELID and EDM processes that has produced surface on silicon with Ra value of 3 nm. It is shown that the ECM has also been used in producing micro features on hard surfaces and features as small as 0.5 μm are developed [48, 49]. Figure 2(e) shows 'Agietron Micro-Nano' die sinking machine that can perform micro drilling to machining of micro-structures with the addition of nano module that can fit on the same machine by replacing the rotary axis of the AGIETRON micro. The nano module is highly agile and uses voice coil linear motors and parallel kinematics for axes movements.

2.1.3. Micro machining through abrasives and lasers. Abrasive micro machining is also explored to develop micro features. The technique is successfully used in the micro-fluidic channels machining [53, 54]. Liu [55] developed a high pressure abrasive slurry jet micro machining equipment and found it a viable technology for producing concave and convex surfaces of optical lenses, with low roughness in variety of materials. Micro machining using lasers or LMM is also in use for industrial micro-engineering applications with different techniques like direct-write LMM [56], CO_2 gas laser LMM [57] and excimer laser LMM [58, 59]. Variety of materials can be used to produce micro features with sub-micron tolerance range using high intensity short laser pulses. Micro molding [60] of plastics also involves micro feature creation like wall thickness up to 80 μm is achievable utilizing high performance plastics and maintaining tolerance of ±5 μm.

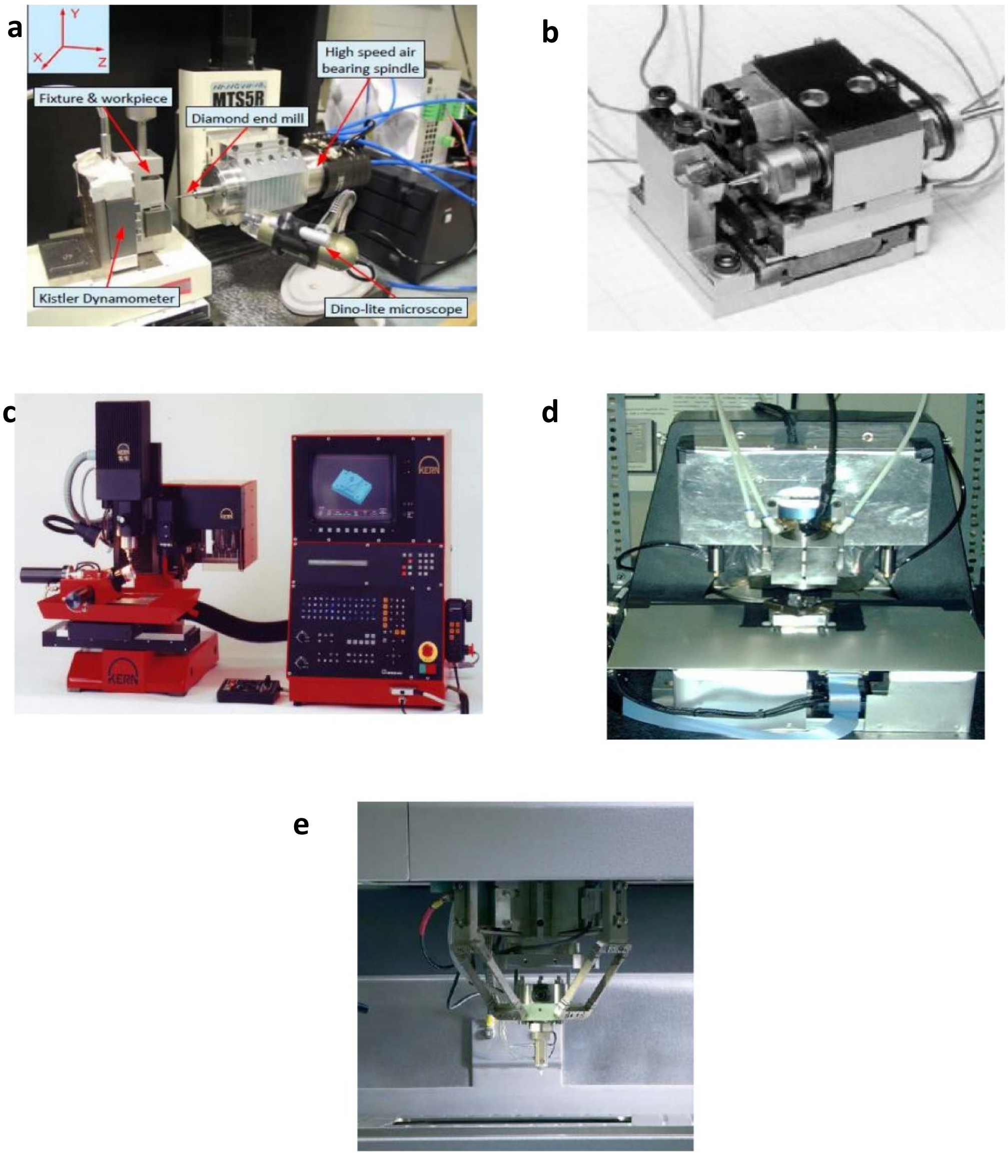


Figure 2. Micro machines (a) MTS5/MTS6 [50], (b) AIST micro lathe [2, 51], (c) micro machine table top model (MMT) developed by KERN, Germany (courtesy of KERN Microtechnik GMBH), (d) micro milling developed in University of Manchester, UK [52], (e) 'AGIETRON MICRO NANO', nano module (courtesy of Agiecharmilles). Reproduced from [50]. CC BY 4.0. Reproduced with permission from [51]. Reproduced with permission from [39]. [KERN Microtechnik GmbH source]. [52] Ogedengbe TI 2010 A Contribution to the Design and Operation of a Micro Milling Machine, PhD Thesis, University of Manchester, UK. Reproduced with permission from [44].

2.1.4. Micro 3D printing. There are optical 3D printing [61] and laser 3D printing [62] additive manufacturing techniques for microfluidics and medicine applications at meso scale as 3D printing currently, is enabling multiple scale features to co-exist on a single artefact [41, 63–65]. FDM are popular 3D printing machines for low cost and high-speed rapid prototyping. However, workable materials are only thermoplastics, that are extruded to form layer over previously settled layer. The finished product has relatively weak mechanical properties with minimum feature resolution range from 50–200 μm [66]. Powder bed fusion is commonly known as selective laser sintering and selective laser melting are fine resolution and high-quality printing in which compacted fine metallic powders are fused using laser scanning. Metals, alloys and some polymers are used in this slow and expansive method. Meso scale applications are employed in biomedical implants, electronics and aerospace with minimum size feature resolution in the range of 80–250 μm [37]. Inkjet printing has made it possible to make large concrete structures using concrete pastes and crafting contours. Ceramics and soil are also in use for such coarse and layered based structural applications. In biomedical implants, inkjet printing has been used with minimum feature resolution in the range of 5–200 μm [37]. μStereolithography printing has the finest resolution available in the range of 10 μm. The process is limited to polymers that are photo active monomers resins. High quality expansive biomedical, electronics and soft robotics related products are printed at a slow rate [66, 67].

2.2. Lithography based meso-micro scale manufacturing

There are different types of LBMM manufacturing processes. LBMM approach patterns the material based on the desired design through either top-down (i.e. surface micromachining) or bottom-up (i.e. bulk micromachining). This approach generally involves lithography that transfers the design onto the material and etching technique that removes any unwanted materials to realize the design. Bulk micromachining is restricted by the substrate which is commonly silicon. The mechanical properties of final components are strongly dependent on the properties of silicon. In contrast, surface micromachining patterns materials that are deposited on top of the substrate (e.g. silicon) and the mechanical properties of final components varies depending on the types of materials that are deposited, such as metals through sputtering and oxides through chemical vapor deposition (CVD).

Lithography is the process by which the patterns are realized in a chemically resistant polymer (i.e. resist) applied by a spin coater onto a substrate [68]. The thickness of resist is dependent on the spinning speed and the viscosity of resist itself. In optical lithography process, the resist is exposed to UV source through a quartz mask with an opaque patterned chrome layer to either break or link the polymer chain. The former is called positive resist (e.g. AZ9245) and the latter is negative resist (e.g. SU-8). After UV exposure, the soluble resist is removed in a development process and the remaining resist is baked in an oven to further harden the chemical links. In contrast, non-optical lithography techniques direct write patterns on to the resist using an energetic beam of electrons/ions across the wafer.

Figure 3 illustrates a standard optical lithography process involving selective removal by selectively etching unprotected materials from the substrate to reveal patterns. After the resist is hardened, uncovered material is then removed by an etching process where the etchants could be either wet or dry. Wet etching is commonly used to remove silicon dioxide, silicon nitride, and the material is removed either in an isotropic or anisotropic manner. Dry etching is achieved using plasma at low pressure and it is a combination of chemical and physical removal. The physical removal process is extremally important in LBMM as it provides anisotropic etch profile with high aspect ratio (e.g. >40:1) in components. Table 4 shows the comparisons of commonly used lithography techniques.

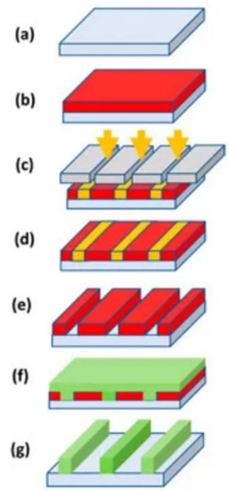


Figure 3. Photolithography process steps: (a) subtractive cleaning, (b) photoresist deposition, (c) UV exposure, (d) post baking, (e) development, (f) metal thin film deposition, and (g) polishing and etching. Reproduced from [69].

2.2.1. Optical lithography. In optical lithography, patterns are created on the resist materials coated on the substrate after the exposure of UV light through a mask and subsequent development processes. Table 5(a) shows Scanning Electron Microscope (SEM) image of a MEMS structure fabricated by optical lithography. The resolution limit of optical lithography is determined from the Rayleigh equation. The resolution limit R and depth of focus (DOF) of a lithographic system are given by the following equations [75]:

$$R = k_1 \frac{\lambda}{\mathrm{NA}} \tag{1}$$

$$\mathrm{DOF} = k_2 \frac{\lambda}{(\mathrm{NA})^2} \tag{2}$$

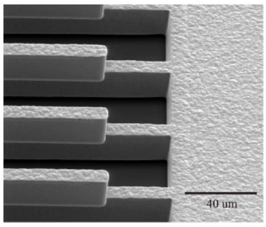
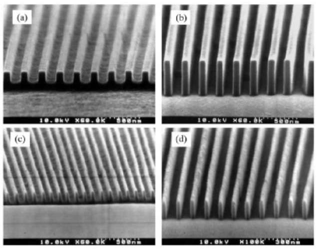
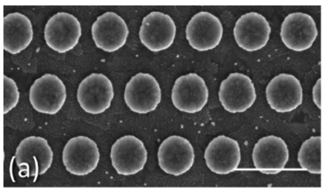
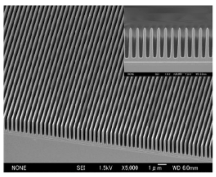
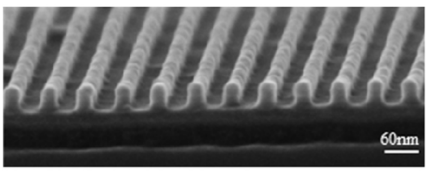
where λ is exposure wavelength, NA is numerical aperture of optical system, k_1 and k_2 are constants that depends on the resist material, process technology and employed exposure technique. For the high resolution, a shorter wavelength and higher NA optical systems and resist resolution are used. The minimum feature size that could be achieved is comparable or slightly smaller than the wavelength of optical system which needs a high NA $\geqslant 0.5$. However, a high NA optical system limits DOF which results in making the exposure process more sensitive to the thickness and absolute position of the resist layer. Thus, leading to the focused beam diverged more rapidly from the focal point [76].

Conventionally, resolution improvements for IC fabrication processes have been achieved by a decrease in printing wavelength i.e. from G-line at 436 nm to I-line at 365 nm as shown in figure 1. Such illumination systems used multispectral lines filtered mercury arc lamp sources. However, an improvement in radiation sources was carried out by excimer lasers at 248 nm and 193 nm with introduction of KrF and ArF, respectively. Moreover, figure 1 shows that progress in minimum feature size is on a much steeper slope to that of lithographic wavelength. With the introduction of 180 nm technology during 1999, significant feature sizes below 248 nm wavelength were achievable [77]. To attain feature sizes less than the wavelength of the exposure system, improvements in imaging resist materials are attributable. The modern resist materials exhibit high imaging contrast and even light intensity is less than full modulation of small features. A combination of

Table 4. Summary comparison between different lithography techniques.

Technique	Mini. feature size	Fabrication area	Fabrication time	Cost	Throughput	Applications
Photolithography (contact & proximity printings) [70]	2–3 μm	Large	Short	High	Very high	Research and production of MEMS devices.
Photolithography (projection printing) [71]	A few tens of nanometers	Large	Short	High	Very high	Research and production of MEMS devices.
Electron beam Lithography [68]	<5 nm	Small	Long	High	Very slow (e.g. 8 h to write a chip pattern)	Mask and IC production.
Ion beam lithography [72]	$\sim$20 nm	Small	Long	High	Very slow	Patterning in R&D including hole arrays and plasmonic lens.
X-ray lithography [73]	$\sim$20 nm	Large	Short	High	High	Research and development.
Extreme UV lithography [74]	<50 nm	Large	Short	High	High	Research and development.

Table 5. Artifacts summary using different LBMM techniques. Reprinted from [82], Copyright (2015), with permission from Elsevier. Reproduced from [79]. CC BY 3.0. Reprinted from [83], Copyright (2012), with permission from Elsevier. Reprinted from [84], Copyright (2012), with permission from Elsevier.

Sr. No.	Techniques	Artifact examples	Explanation
1	Optical lithography		SEM image of a MEMS structure fabricated by optical lithography.
2	Electron beam lithography		Development of HSQ dense parallel lines using lithography at different developing temperatures. 100 nm (a and b), 30 nm (c and d) line-width and 100 nm pitch [82].
3	Ion projection lithography (IPL)		SEM image of Ag nano disks fabricated by ion beam lithography [68].
4	Proximity x-ray lithography		Examples of structures fabricated using proximity x-ray lithography [83].
5	Extreme ultraviolet lithography (EUV)		CD-SEM, cross section images of 32 nm half pitch resist lines/spaces structure after lithographic exposure [84].

resist material imaging contrast and process control can reliably achieve subwavelength features and consequently reduce the value of k_1.

2.2.2. Electron beam lithography (EBL). EBL use a fine focused electron beam that has the capability of extremely high resolution with a large DOF. It is used to fabricate the masks and reticules for optical lithography. Owing to its high-resolution, it is used for fine scale devices for fundamental and device verification and high operating frequency devices [78]. The largest problem with EBL system is its low throughput due to slow scanning of electron on the surface and inability to employ for the mass-produced LSI circuitry.

There has been a considerable interest to increase the throughput of EBL by enlarging and shaping the electron beam, for example to vary the size and shape of electron beam during writing process. The efforts have put-forward to ensure writing time insensitive to the minimum feature size i.e. coarser features can be written with a larger beam during a single pass. Furthermore, several areas of the pattern need to be exposed simultaneously [76]. Table 5(b) shows scanning electron microscopic image of electron beam direct write on UVIII resist to achieve chiral structures.

2.2.3. Ion Projection Lithography. In IPL, the electron beam is simply replaced by an accelerated ion beam to directly punch a metallic film on the substrate, as a result of the heavy mass of ions compared to that of electrons. Due to much high mass, the beam is less prone to distortions owing to backscattering from the substrate and results to improve the imaging capabilities of the lithography system. The resolution of ion beam lithography techniques is of the order of 5–20 nm due to ultra-short wavelengths of electron/ion beams in the order of a few nanometers. The lack of throughput limits their applications within research and mask fabrication. However, the high-resolution ion beam systems are in a primitive state of development compared to electron beam systems. Table 5(c) shows an example of silver nano disks array fabricated on a glass substrate by ion beam lithography [79].

2.2.4. Proximity x-ray lithography. Comparing with optical wave, x-ray penetrates the vast majority of materials except those with much higher atomic numbers and there is no refraction after x-ray enters the materials. The x-ray exposure can only be 1:1 with a proximity gap between mask and resist [80]. In the proximity lithography, the mask is placed in close proximity to the substrate and the pattern is produced by the shadow of the mask on the semiconductor substrate during exposure. In a proximity x-ray system, the x-rays are first collimated using a mirror of silicon carbide and then allowed to pass through a transparent window of beryllium into a chamber containing the mask and the semiconductor substrate. The mask is usually produced on a membrane of low atomic number materials (e.g. silicon carbide) which are transparent to x-ray, while materials with higher atomic numbers (e.g. Au and W) can effectively block x-ray such that the patterns are generated by patterning those high atomic number materials. Table 5(d) shows examples, fabricated using proximity x-ray lithography with critical dimensions between 100 nm and 150 nm [81]. Although the proximity x-ray lithography is a good candidate for NGL process in LSI, there are still lots of challenges that need to be overcome, such as precise gap control between mask and resist.

2.2.5. EUV lithography. EUV lithography is used to produce extremely small pattern of ⩽45 nm and below. EUV lithography uses the exposure wavelength of 13.5 nm and photons that are obtained from plasma source. The technique is based upon the similar principle as the conventional optical projection lithography and obeys Rayleigh equations for system resolution. At such a small wavelength region, the absorption of light is very strong that cannot makes the use of refractive optics and instead, employs all the reflective optics [85]. Furthermore, in all reflective optics, the conventional mirror surfaces cannot be used. Therefore, one must use the multilayer structures that rely on interference principle to show a reasonable reflectivity. However, the obtained reflectivity is around 60%–70% at these wavelengths. Table 5(e) shows dense patterns of tilted cross-section SEM images after Cr and W etching by EUV lithography [86].

The improvements in lithographic resolution and edge contrast were achieved with improvements in exposure tools (projection lens), decrease in exposure wavelengths and photoresists which results in projection photolithography. In this projection system, the lens is used to focus the mask patterns to smaller areas. Therefore, state-of-the-art current projection systems can achieve resolutions down to a few tens of nanometers [71]. Moreover, projection lithography is aligned with complex systems which are widely less available and are not cost-effective solutions in comparison to contact and projection photolithography.

2.3. Meso/micro scale manufacturing using combined approach

A new approach targeting meso/micro-scale manufacturing is to develop micro artefacts by employing NLBMM and LBMM techniques in a simultaneous way. The meso scale fills the gap from sub-10 μm to near 300 μm features [87]. Meso scale products can take advantage in such that the features produced from one technique can be finished using the other technique. This can be considered as a combined approach that can fall within the range from sub-micron to the meso scale. Below 10 μm manufacturing regime covers the semiconductor, and other nano-manufacturing processes like direct writing techniques through laser and other additive manufacturing processes [88] and fabrication in micro and nano-manufacturing. On the other side, high precision NLBMM are employed beyond 300 μm manufacturing regime. There are a mix of approaches which can cover the gap areas and are termed as combined approach in this work as shown in figure 4.

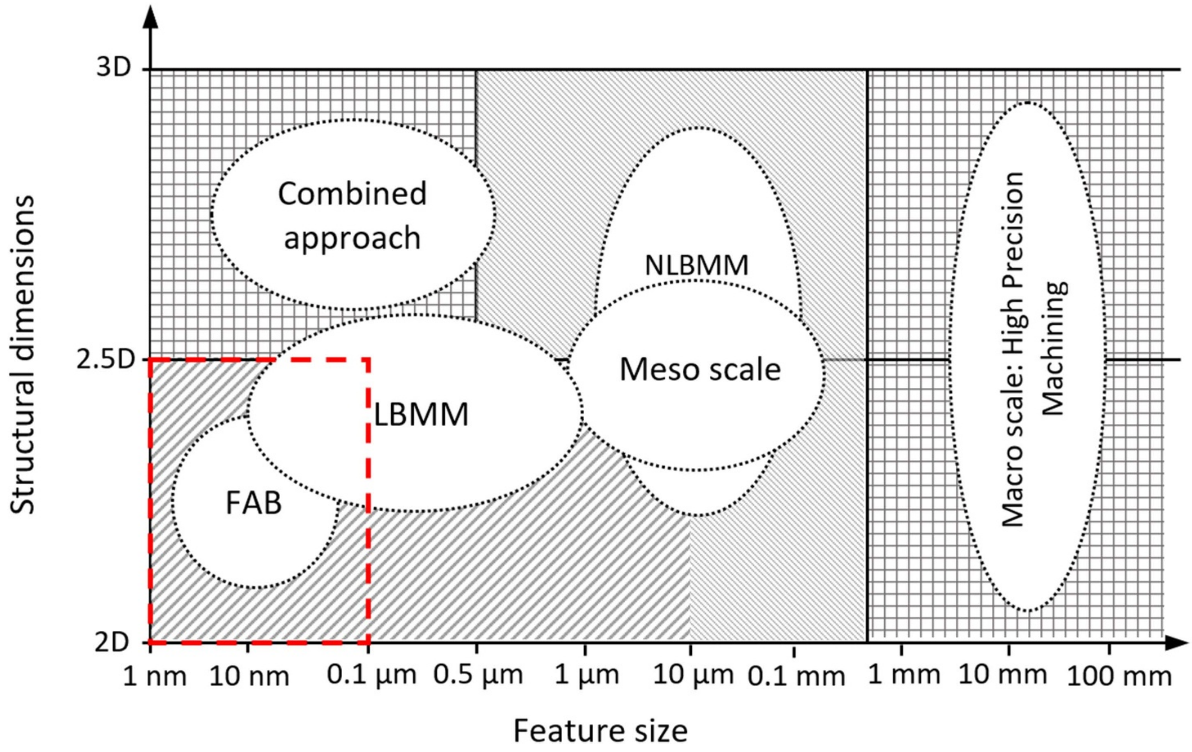


Figure 4. NLBMM, LBMM and combined micro fabrication specific zones.

Meso scale regime is a buffer region where the characteristic features from the bordering scales can be employed. There are examples of combining LBMM and micro EDM from NLBMM to fabricate microstructure in tungsten carbide for micro tools and other micro features involving high aspect ratio [89]. Fabrication of soft polymers using photolithography presents a potential area for combined manufacturing approach in which lab-on-chip devices are fabricated for medical applications. These are popular products for biologists to discover new drugs, clinical assessments, cytometry and optimal dosage experimentation. Lab-on-chip microfluidic device contains microchannels for functions of mixing, filtering and analysis. Silicon or glass substrates are commonly used to produce fluidic chips by deposition of metallic layers and subsequent photolithography for pattering of layers to outline microchannels. The process is completed by etching to reveal desired structure. Other alternative is to do micro milling of the metallized substrate to reveal electrodes [90]. Some examples of combined approach in electronic industry include LMM of polymer substrate, micro drilling of holes, patterning and scribing in lab on chip devices and wafer substrates, micro features fabrication in MEMS and ultrasonic machining for semiconductor component slicing and trimming. Other example includes the bespoke patterned micro tools fabricated through lithography are used in die sinking electro chemical machining for manufacturing of complex profiles [89–91].

There is a potential for some LBMM and NLBMM approaches that can be combined to form meso-scale 3D features. In this regard, LBMM consists of processes typical to semi-conductor processing in which, for example, a film is deposited via vapor deposition techniques followed by chemical or reactive ion etching. For example, bulk micromachining, surface micro machining and direct ceramic machining with the support from WEDM has the potential for 3D meso-scale manufacturing having capability of handling multiple materials [92]. The applications include surgical instruments on the meso scale like cardiovascular stents, lab on chip devices and micro needles that can be fabricated using LBMM and further/alternative processing can be done through micro wire EDM, LMM and electroforming, micro ultra-sonic machining (MUSM) and micro-ECM. MUSM is also used as a functional device where the ultrasonic cutting tool actuated by piezoelectric actuator for the cutter to resonate [93] and cut through tissues like hardened lenses with cataracts.

In most of the examples considered, NLBMM is used either as support/finishing process or identified as an alternative method to produce 2D/3D micro artifacts. Other examples are complex 3D shapes, such as V-grooves, channels, pyramidal pits, membranes, vias, and nozzles are formed through bulk micro machining [94]. In bulk micromachining, the substrate material, which is typically single-crystal silicon, is patterned and shaped to form an important functional component of the resulting device. There are ways to form micro channels using cutting plotter blades to develop lab-on-chip device for blood sampling and analysis [95]. Micro needles are developed with different materials like in stainless steel [96] using femtosecond LMM for drug delivery to diabetic rats. Other manufacturing methods are employed for polymer micro needles using bulk lithography, droplet borne air blowing and injection molding [97, 98]. These examples are discussed as the potential manufacturing process options to be used for same type of products. As a fully developed combined approach, ECM is integrated with dry etching of photoresist to reduce the size of tip opening. The gold dot patterns are then produced after lithography with a dimeter of 200 nm [99].

Stereolithography based 3D printing [100] is another approach gaining popularity for tissue engineering and developing bio materials at different size scales. The technique combines the flexibility of 3D printing with a laser light source to cure liquid resin into hardened form, thereby, avoiding pattern and mold requirements, an effective way to make cavities and freestanding structures. In order to further improve the structural properties and making the parts functional (electrical conductivity), SLA printed parts are metallized through sputtering/CVD and further chemically etched [101, 102]. The process can be applied to different types of polymers, that enables metallization of polymer parts, making easier to manufacture printed circuitry. The etching provides uniform coverage of metal coating, even on hard to access zones of the complicated, small size, 3D parts. Overall, this has developed into an important meso scale application in which CVD and etching are followed, once the part is printed using SLA, making it a truly combined approach.

3. Comparative analysis

While looking at the NLBMM, LBMM and the combined approaches, it seems obvious that there are specific size scales and other associated issues that can be identified for a particular approach. As discussed, most NLBMM techniques are downscaled in tabletop size machines that can manufacture features in micron scale with higher accuracies in an energy efficient way. The LBMM techniques were established to fabricate micron size devices and features and now the feature resolution has reached to the nano scale. A comparative study is conducted to compare the effectiveness of each approach. The feature size, capability to manufacture variety of shapes, use of various engineering materials, production rates, attainable accuracies and required investments are some of the important factors to be included in comparison. Table 6 shows the comparison of the three approaches. The comparison table shows that NLBMM processes have a dominant role at micron scale. In contrast, modern day LBMM techniques are mostly utilized for achieving nano scale resolution as required by the semiconductor industry.

As getting the right size, tolerances and shape is important for meso scale features, therefore, many overlapping multi-scale manufacturing options are studied and compared. The criteria developed for the comparison of the three techniques is focused for the meso-scale features and products normally used in application of medical devices, watch and electronics industry. NLBMM processes are suitable for development of two and three-dimensional intricate parts having micron size features in traditional materials. As a concept, NLBMM processes employ subtractive machining or material removal technologies except 3D printing for meso-scale products and features. Subtractive NLBMM processes have the potential of expanding the manufacturability of meso-scale components and complement LBMM and additive technologies. Examples of medical devices like micro-needles are already discussed in the combined approach section.

As far the achievable accuracies are concerned, both the techniques are comparable attaining nm level surface roughness and accuracies. Most of the NLBMM processes are suitable for batch manufacturing, hence, low to medium level production of meso-scale artifacts is viable, however, the production rates are heavily dependent on the feature complexity. As an example, the machining time for any drilled hole in micro artifact shown in table 2 (example 1) is 7.8 s. On the other hand, the established products using LBMM can be mass produced at a very high rate. For the comparison of initial capital investment and operational costs, it is relatively cheaper in case of NLBMM to establish a new production line. Another feature is the process re-configurability in NLBMM as multiple micro machines can be re-configured to produce small batch production. Batch production in lithography-based device manufacturing is common that is based on the development of specific tooling and the cost variation depends on the application. In LBMM, short wavelength optical lithography and the use of new materials including biomaterials are the new trends. In NLBMM, machine tool designers are employing innovative mechanisms like parallel manipulators, machine re-configuration, sequential micro machining [121] using a single machine tool and intelligent machine systems.

4. Challenges for NLBMM and LBMM

At the meso-scale, both the LBMM and NLBMM seems to be viable options for various types of applications. However, there are number of challenges in both the techniques that are needed to overcome. The challenges include development of new products at the meso-scale, their design and materials involved relevant to the production process, metrology techniques, packaging, contamination, assembly and self-assembly in addition to modeling and scaling laws at meso-scale, to name a few. The factors are discussed in detail for both the cases with a view of improvement in processes in future.

4.1. Challenges for NLBMM

As NLBMM is a developing technology in the domain of micro/meso scale manufacturing. The issues for the cost-effective implementation of NLBMM need to address the following concerns.

4.1.1. Ultra-precision machinery. The high-end UPMs are designed with features having tight specifications in terms of friction less drives, moving parts with extremely high resolution, repeatability and position stability of dynamic system. The biggest challenge is the cost effectiveness of the manufacturing process using such machinery for meso-scale components that are manufactured for applications like microfluidics, photonics, energy harvesting and miniature devices. High resolution components in both linear and rotary stages

Table 6. Comparison of three approaches for meso-scale manufacturing.

Process characteristics	NLBMM	LBMM	Combined approach
Processes	μECM, μEDM, μWEDM, μUSM, μmilling, μturning, LMM, μmolding, abrasive μ machining.	X-ray, e-beam direct write (EBDW), extreme UV (EUV), electron projection (EPL) and ion projection lithography (IPL) [78].	Bulk micro machining with WEDM, LMM and micro drilling, cutting [103]. SLA with CVD and chemical etching.
Applications only in meso scale	Watch industry, medical devices, sensors, micro actuators, micro pumps.	Medical devices, micro actuators/sensors, micro electronics.	Surgical devices, lab-on-chip devices, micro-needles [104].
Minimum feature size	Meso-scale (few microns to few mm).	Up to 50 nm for most of the semi-conductor industry. Both micro and nano scales are commonly achievable [77].	Employed at micro meso scale (see figure 4). 10 μm size features are possible with SLA that can be further processed to make functional parts [102, 105].
Feature shapes	Complex 3D shapes are commonly manufactured at meso micro scale.	2D, 2.5D up to 3D geometries with slender, hollow and free-standing structures [106], but 3D capabilities are limited.	3D is possible depending upon the selection of major process. Most common with SLA 3D printing.
Process materials	Almost all engineering materials used in large scale manufacturing can be processed at meso scale.	Silicon, metals, oxides, semi-conductors and hydrogels [107].	Variety of engineering materials including polymers, metals and ceramics.
Production rates for meso scale manufacturing	Low to medium scale production is possible. Mainly depends on machining time, feed rate, speed etc [108]	Mostly mass production processes.	Application specific. Low to medium where major portion of the process includes NLBMM or stereolithography.
Feature accuracy at meso scale	$\pm$1 μm–$\pm$2.5 μm in meso scale manufacturing. Further accuracy range is achievable using ultra precision machinery [109].	$\pm$1 μm–$\pm$100 μm [110].	$\pm$10 μm–$\pm$50 μm, using stereolithography based 3D printing technology [111].
Process resolution	0.02 μm–0.1 μm [44].	0.1 μm–1 μm [68].	For different types of stereolithography: 10 μm–100 μm [112].
Process initial investment	Price for high precision CNC micro machine tool can range from 40k–70k USD [52]. Mainly depends on the required precision. Large size machines can cost more.	Capital investment for lithography based fabrication equipment \$20 million–\$100 million [68, 113].	SLA printers costs from \$5k–\$15k. No extra investment required in case LBMM and NLBMM process equipment are installed.
Tooling/consumables cost	Cheap consumable tools e.g. micro end mill cutters are available from 80–1000 μm. [50]	Costly molds and tools specific to the feature size. Consumables cost can reach upto \$2–\$3 million yr^{-1}. [114]	In stereolithography 3D printing, material and tooling can cost up to \$30–\$40 per hour of print [115].
Operational costs	Energy, labor and other overheads for three axis CNC machine operational cost: \$35–\$40 per hour [24, 116].	\$50k–\$500k per mask. Mask utility is based on the number of exposures per mask [114].	Using stereolithography 3D printing, energy, labour and overheads can cost up to \$50–\$60 per hour of print [115].
Process re-configurability	Process re-configuration in CNC machining centers for batch production.	Costly tooling specific to the feature or device. Phase-change material photomasks are employed to optically reconfigure mask pattern on demand [117].	Using SLA 3D printing, multi material process reconfigurability is possible [118].
Functionally active parts manufacturing	NLBMM processes are known for manufacturing of passive parts. However, shape-memory alloys are made by casting.	LBMM has limited capability to produce active parts using shape memory materials [119].	Stimulus responsive shape memory polymers create functionally deployable, lightweight metamaterials using 4D printing approach [120].

are a must requirement for NLBMM production equipment. Actuation components including high torque motors in small packaging and high-resolution encoders that can resolve 1 nm are required in moderate price range for production and economic manufacturing of meso-scale parts, products and features. It is also important that for a fixed control memory bit, a small machine's stage can have a better spatial resolution than the large machine axis [7]. For precision mechanics, the micro stages are designed with unconventional designs using parallel kinematics [122], flexures [123], serial-parallel hybrid axis [4, 124] and using shape memory alloy [125], though not commercialized on a mass scale.

4.1.2. Micro components. It is expected that the demand for meso-scale 3D components and features will increase in various industries from electronics to biomedical. Precision micro stages, micro spindles, motors in small packaging, micro actuators, micro tools, small scale fixtures and handling devices are the key components in NLBMM production machinery. Software technologies include machine tool components with suitable control algorithms as well as an understanding of process physics is needed. As an example, ultra-precision positioning systems with 1 nm positional resolution are developed by Otsuka *et al* [126]. A magnetic bearing based stage of 0.1 nm resolution is developed by Holmes *et al* [127]. A 25 pm positioning resolution system is developed by Mizumoto *et al* [128, 129] using twist roller drive and aerostatic guide way. Friction roller drive is invented by keeping the drive roller at a very small angle to the driven roller. Vacuum chucks are proposed by Qiao and Bu [130] for handling of micro parts. Micromachining requires very high-speed spindle speeds due to small tool diameters that can cause large centrifugal force during spindle rotation, can create massive radial loading conditions for precision bearings. For micro actuators and stages, use of piezoelectric actuators are the choice in high precision micro stages in addition to the precision mechanisms.

4.1.3. Micro factory. NLBMM productivity can be enhanced by developing micro factories [2, 24, 131] that consists of high precision micro machines and associated equipment. Associated equipment also includes the working environment in which the micro machines work, e.g. a desktop clean room, a centralized control system and other modules are developed [132–134]. However, the biggest challenge lies in the fabrication of the proper tool geometry for creating various 3D features. The other issue is the micro factory compatibility to accommodate multi-scale components for assembly processes.

4.1.4. Multi-scale physics. Physics at micro/meso scale has different effects as compared to the macro scale. The fundamental difference lies in the influential surface forces as compared to the smaller inertial forces [24, 135, 136]. This results in the development of many handling, inspection and manufacturing devices at a small scale. The micro machined products cannot be reliably produced without sensor-based metrology and measurement techniques. Due to the small scale of products, it is necessary to use non-contact measurement [137] techniques for precision quality products. This will reduce the damage to parts and improve inspection rate to enhance productivity. Fabrication of smaller features with reliability at high tolerance also requires visual and in-process inspection techniques [137, 138] of micro parts. The additional challenge in such products is the assembly of multi scale parts as this type of assembly needs special fixtures and tools.

4.1.5. Sensors. Conventional manufacturing machines utilize a lot of sensors which cannot be effectively used due to practical considerations, if meso scale parts are produced using high precision micro machines. The sensors can be divided into three applications areas in micro-meso scale manufacturing. These include sensors used in CNC machine operation, sensors for metrology and in-process inspection and sensors employed for condition monitoring and health assessment of manufacturing machines. Large size sensors like limit switches, encoders, read-heads, linear scales and other transducers cannot work on high precision small scale machine. To cater for micro machines, small size, high resolution, high precision and reliable sensors need to be selected.

Micro machine and micro artefact metrology for measuring micro features is another challenging area. The main technical issues are artefact/feature damage due to contact and micro feature size smaller than the measuring probe itself. Non-contact vision based [137, 138] techniques are in development to cater for faster measurements. These devices in addition to other such non-contact sensors like ultrasonic, LIDAR and radar-based sensors connected through IoT are a necessity if large amount of data has to be collected and processed. Another application area is emerged with the development of micro metrology devices [139], micro probes and even complete micro coordinate measuring machine (CMM) systems. E.g. a micro CMM is developed with a resolution of 1.3 nm [140]. Micro probes are another necessity in micro feature metrology, in fact one of the two effective solutions. The solution is either the development of micro probes and tactile sensors smaller than the size of the features or a complete non-contact metrology system that can extract the features with high accuracy from the image. Non-contact ultrasonic and acoustic emission-based sensors are also in use in such applications [141].

In today's new manufacturing paradigm of IoT enabled production systems, micro machines need to be integrated on network and ultimately to the cloud for smart manufacturing of micro products. In-process inspection of micro tools and micro artefacts/features and condition monitoring of machines can generate large data sets that can become a big data problem to predict better maintenance schedules of micro machines and micro factories.

4.1.6. Micro tools. NLBMM needs all types of micro tools to run the processes on smaller scales, but there are typical issues involved. First to achieve a micro tool geometry is a challenging task for diameters of less than 50 μm. Simple geometries in less than 50 μm diameter are available in drill sets [7], but milling cutters in these sizes are still not commercially available. Even, if the complicated tools are fabricated to cut 3D micro features, the micro tool working environment needs to be controlled very strictly in order to avoid tool breakages. Micro tools have limited use when cutting hard to cut materials. Cuts with large speeds and feeds are generally not possible, however, improved chip removal can result in better finish [142]. A micro ball-end mill [143] is designed to machine gold using 5 axis machining as an example of improved chip removal. Thermal stresses can be fatal in the micro tool as fast heating and cooling takes place due to small cross-section sizes. Effective cooling mechanisms, in-process inspection and condition monitoring of micro tools [144] are in infancy stage of research.

4.2. LBMM issues and challenges

Lithography is a key microfabrication technology as it determines the dimension, quality and quantity of the device. Miniaturization is a drive-in recent development and commercialization such that many components (e.g. Sensors, CPUs) are getting smaller and smaller. As the feature size decreases based on the Moore's law, fabricating small features become increasingly difficult as well as the cost and functionality of the fabrication process. The requirements of microfabricated devices are reliability, low power dissipation, low cost, coupled with an ability to integrate with a high degree of sophistication and complexity. Reliability is the key element for a microfabricated device being used for a long period of time without any fault and errors.

4.2.1. Contamination issue. Any contaminants, such as dust particles suspended in air, may compromise the reliability of the entire system. All reliability issues concerned with microfabrication are directly and indirectly related to the clean room technology environment. The clean room is a workplace where the air quality, temperature and humidity are highly regulated in order to protect sensitive equipment from contaminations, native oxide growth, dust particles and other related harmful factors and it is crucial in case of lithography.

For photolithography, the main concerns over the various cleaning issues include the photolithography mask, photoresist and etchant used, and silicon wafer itself. The primary sources of defects are airborne contamination, such as small dust particles (invisible by naked eye), increased amount of molecular organic materials like amines that resists cleaning materials. The detection of these contaminants and their effect on yield loss is a challenge to the industry.

4.2.2. Resolution issue. The fundamental limitation in optical photolithography is the trade-off between speed and resolution [145]. Non-radiation patterning has their own challenges. For example, mechanical patterning such as nanoimprint is a form of contact lithography, facing issues of defect density, mask cost, mask damage, and wafer throughput. The throughput is an important issue in EBL, whereas the DOF is a main issue in optical lithography, and investment cost is the major issue in x-ray lithography. The dimensions of microfabricated device will continue to shrink as the scaling enables higher speed and greater density. Lithography equipment, resist processes, and mask-making will keep changing to meet the challenges.

4.2.3. Cost issue. The high price of exposure tools has made the cost of lithography a concern and lithography costs may ultimately limit patterning capability. To meet the demands of the consumer, lithography will need to be cost-effective, in addition to providing technical capability. Lithography tools are often the most expensive investment in a cleanroom. Even when they are not, the fact that lithography is required for patterning many layers in microfabrication process, while most other tools are used for only a few steps, means that a large number of lithography tools are needed for each cleanroom, resulting in high overall total costs. Wafer steppers are the most expensive pieces of equipment in the lithography tool set. Their prices have increased by an average of 17% per year since they were introduced in the late 1970s, to the point where leading-edge step-and-scan systems now cost close to $20 M, and their prices are projected to increase in the future [113].

4.3. Issues and challenges in combined approach

Meso and micro scales are appropriately dealt with in the combined technique as examples exists in the form of lithography followed by abrasive machining and lithography followed by welding, bonding and finishing processes [104, 146]. The combined approach is not yet a formal manufacturing classification, but there are a growing number of applications especially in medical devices. A developing field of research is the flexibility of processing multiple materials in case of stereolithography 3D micro printing. A variety of materials can be employed using stereolithography and other combination of techniques, however, tackling low production rates and material strength issues are a challenge.

5. Process effectiveness guideline

A guideline can be discussed after looking at the NLBMM and LBMM issues and technical challenges with regards to the future trends. Though the two techniques have their specific zones with regards to scale and feature dimensional and shape complexity, there is a potential for combined approach as well where any of the two techniques can work as the baseline technique with the other one as a finishing process. Figure 5 highlights an overlapping zone where the three approaches can overlap. The zone reflects the meso scale with 3D features, where NLBMM can be used with variety of materials, however, LBMM techniques are being used to make very slender, irregular 3D shapes, hollow or freestanding structures.

With the advent in IoT based technologies, manufacturing of low-cost sensors and MEMS are further pushing the demand for large scale production. This will increase in micro machining requirements of ceramics, piezo and other sensor

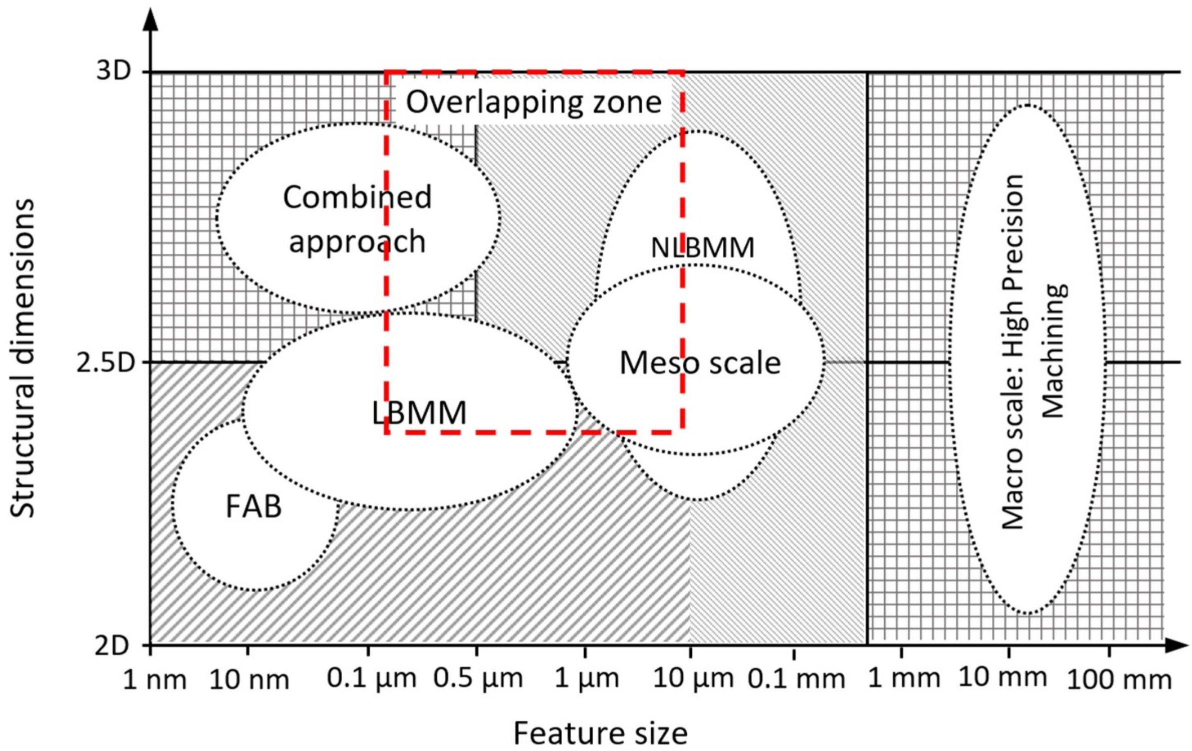


Figure 5. Overlapping zone.

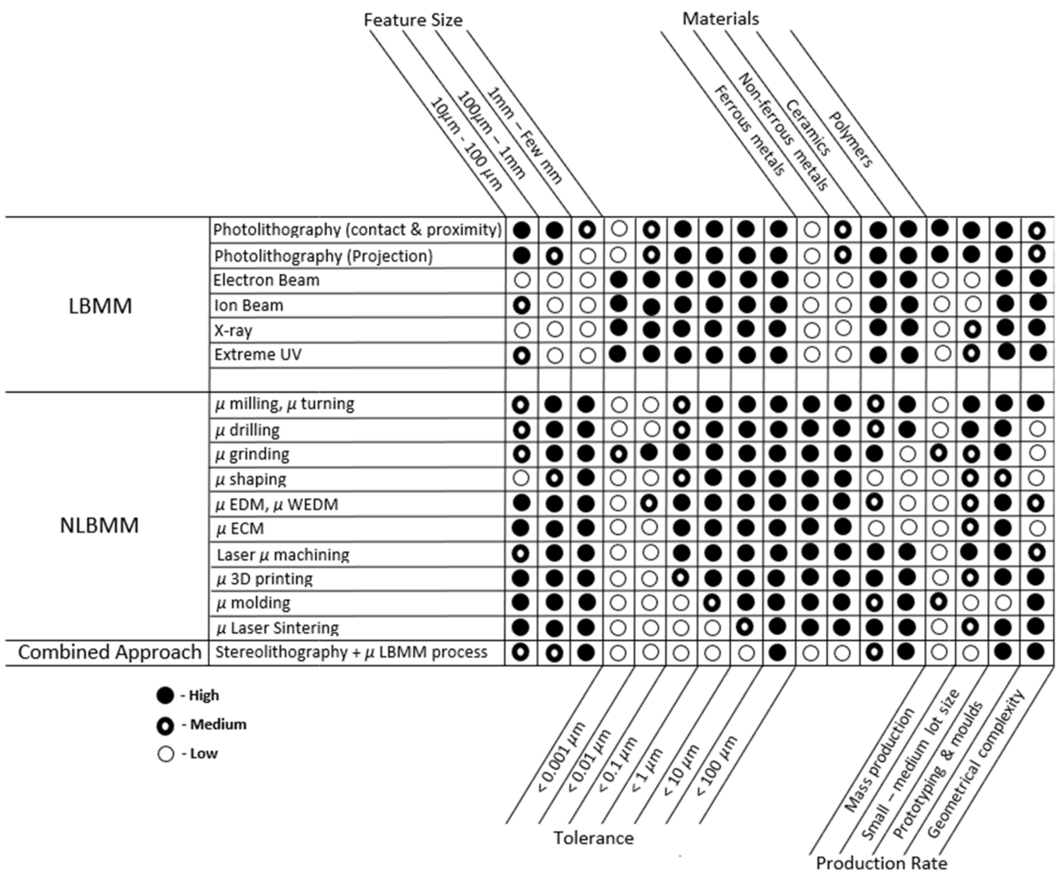


Figure 6. Overall summary: process effective guideline for meso/micro manufacturing.

materials and hence, the new technologies in overlapping zone are possibly emerging. This overlapping zone can be considered as the window of opportunity in the future of micro-meso scale manufacturing as meso scale assembly can employ components built through numerous processes of NLBMM, LBMM and combined approaches with materials flexibility, cost effectiveness and multi scale component integration for diverse applications.

When NLBMM techniques go beyond micro-meso domain, the challenges increase with further reduction in size. In contrary, for modern day LBMM processes, the normal feature size has reduced in the range of 10–50 nm. Figure 6 reveals an overall guideline for the NLBMM, LBMM and combined approach processes in terms of feature size, achievable tolerances, materials and production rate. Each category is further divided into few sub-categories for detailed working like feature sizes are divided in to three ranges of micro and meso scales. Similarly, achievable tolerances are divided into six ranges from nano to micro-meter. For materials, ferrous, non-ferrous, ceramics and polymers are identified and for production rate, prototyping to mass production is categorized. A total of six LBMM, ten NLBMM and one combined approach process is tabulated. There are three categories defined for low, medium and high effectiveness with the process.

The trend shows that micro NLBMM processes are more relevant in meso scale, but they are not suited in mass production. There is a mix pattern for the achievable geometrical complexity in micro meso scale features for both NLBMM and LBMM. A recent development is the ability of LBMM and stereolithography processes combined to make functional components at micro meso scale has created an edge and found as a fully developed combined approach. Sputtering and CVD are used to deposit metals and non-metals materials onto SLA built polymer substrate to make them functional by finishing through chemical etching. On NLBMM side, micro 3D printing is employed recently for development of functional components and manufacturers are looking for mass production of micro 3D printed functional parts as the new way forward. Flexible 3D printed assemblies and fabrics have the potential in textile, fashion and medical industries. Some examples of 3D printed functional assemblies are ball & socket joint, bearings and functional hinges and chains. Stereolithography based 3D printing is the most advanced process for detailed concept models with better finish for functional and non-functional parts.

6. Conclusion

The study in this paper by comparing lithography versus NLBMM reveals different manufacturing options for a given requirement. It is concluded that some of the present day NLBMM techniques are in nascent stage but have a promising future. Various 3D micro products have been attempted in NLBMM with a very high accuracy level. Although, the micro products like semi-conductor and MEMS devices have not taken considerable attention by NLBMM techniques, as these applications are widely served through LBMM based techniques. The focus of LBMM processes is more towards micro and nano scale, therefore, meso scale is still exploited by more NLBMM and stereolithography approaches. Manufacturers are employing ways to increase the production rates to cater for high demand of meso scale parts and products. The cost effectiveness of NLBMM processes for production of meso scale parts can be enhanced, if the technological development can made possible for the availability of cheaper high precision machinery.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

The authors would like to acknowledge the support of KERN-microtechnik, Germany and Boston Micro Fabrication, USA for their support in providing artifact sample figures. Certain images in this publication have been obtained by the author(s) from the Wikipedia/Wikimedia website, where they were made available under a Creative Commons licence or stated to be in the public domain. Please see individual figure captions in this publication for details. To the extent that the law allows, IOP Publishing disclaim any liability that any person may suffer as a result of accessing, using or forwarding the image(s). Any reuse rights should be checked and permission should be sought if necessary from Wikipedia/Wikimedia and/or the copyright owner (as appropriate) before using or forwarding the image(s).

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