Meso-scale Machining Capabilities and Issues

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ABSTRACT

Meso-scale manufacturing processes are bridging the gap between silicon-based MEMS processes and conventional miniature machining. These processes can fabricate two and three-dimensional parts having micron size features in traditional materials such as stainless steels, rare earth magnets, ceramics, and glass. Meso-scale processes that are currently available include, focused ion beam sputtering, micro-milling, micro-turning, excimer laser ablation, femto-second laser ablation, and micro electro discharge machining. These meso-scale processes employ subtractive machining technologies (i.e., material removal), unlike LIGA, which is an additive meso-scale process. Meso-scale processes have different material capabilities and machining performance specifications. Machining performance specifications of interest include minimum feature size, feature tolerance, feature location accuracy, surface finish, and material removal rate. Sandia National Laboratories is developing meso-scale electro-mechanical components, which require meso-scale parts that move relative to one another. The meso-scale parts fabricated by subtractive meso-scale manufacturing processes have unique tribology issues because of the variety of materials and the surface conditions produced by the different meso-scale manufacturing processes.

INTRODUCTION

Sandia National Laboratories has a need to machine meso-scale features in a variety of materials. In the past, Sandia has developed precision miniature-scale electro-mechanical components. Presently, Sandia has been developing functionally similar electro-mechanical components using technologies such as silicon based MEMS and LIGA. The authors recognized that there was a void in our ability to fabricate meso-scale parts and features. There is also a need to machine meso-scale features in traditional engineering materials like stainless steels, ceramic and rare earth magnets. Examples of meso-scale features are, fillets, spherical radii, contours, holes, and channels. **Figure 1** is an illustration of the relative size of critical dimensions for miniature, meso, and micro machining. In general, meso-machining processes should be capable of machining feature sizes of 25 microns or less. Unlike LIGA which is an additive technology, the meso-machining technologies that are being developed are subtractive in that material is removed to fabricate a part. These subtractive technologies are, focused ion beam machining, micro-milling, micro-turning, laser machining, and micro electro-discharge machining. Sandia is driven to develop micro- and meso-scale fabrication technologies to meet the needs of the nuclear weapons stockpile.

The focused ion beam (FIB) machines metals by bombarding the work piece with a nanometer scale diameter beam of gallium ions. The material removal rate for focused ion beam machining is very low, on the order of 0.5 cubic microns per second. Given the low material removal rate, the effort is placed upon fabricating tools that can be used repetitively to remove material at much faster rates. Examples of these tools are 25 micron diameter end mills, masks for photolithography and masks for laser machining. Sandia has successfully milled square channels having a cross section of 25 microns by 25 microns in PMMA, aluminum, brass, and 4340 steel using a high precision milling machine. The work related to using the FIB to fabricate hard tooling, has been a joint effort between Sandia National Laboratories and Louisiana Tech University.

The two laser machining processes that are being developed are nanosecond excimer and femtosecond Ti-sapphire. The excimer laser, which has a nanosecond pulse width, can readily machine meso-scale holes and channels in polymers and ceramics. A mask projection technique can be introduced in the expanded portion of the excimer laser beam to project a complex de-magnified replica of the mask onto the workpiece. The femtosecond Ti-sapphire laser can readily machine micro-scale holes and channels in metals. The femtoscond laser machining process can fabricate a one micron diameter, high aspect ratio hole in metal with minimal debris. Laser machining can be used to create three dimensional features because depth of cut is very well correlated to exposure time.

Sandia's Agie Compact 1 micro-sinker electro-discharge machine (EDM) is being used to machine features as small as 25 microns in difficult materials such as stainless steels and kovar. This class of EDM technology employs a micro-generator that is capable of controlling over-burn gaps to as little as three microns. LIGA technology is being employed to fabricate small intricate copper electrodes. These are mounted to the micro-sinker EDM to machine the complementary shape into these difficult materials.

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These subtractive meso-scale machining technologies generate issues in regards to cleanliness, assembly, and tribology. Some issues are unique to meso-scale machining while other issues can be regarded as an extension of similar macro-scale issues. Cleanliness is important because meso-scale critical dimensions can easily be exceeded by dirt particle size or debris created during the machining process. Meso-scale milling and turning can create chips and burrs that can block holes or create a mechanical interference. Surface morphology and surface finish conditions vary greatly depending upon the meso-scale machining technology. The great variety of materials and surface conditions create a complex parameter set for characterizing tribological phenomenon. Meso-scale parts are difficult to handle and align which makes assembly a challenge.

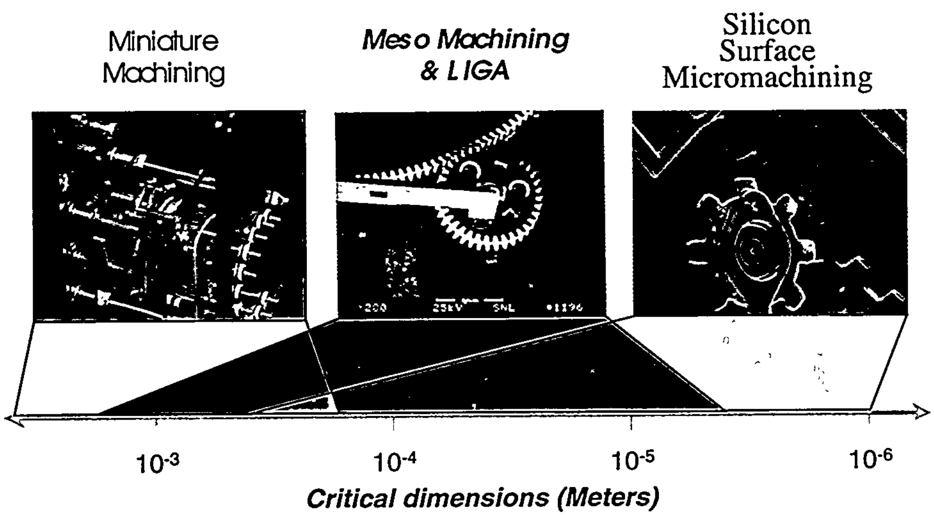

Figure 1: Perspective of miniature machining, meso-machining, and micro-machining.

MESO-SCALE MACHINING PROCESSES

Focused Ion Beam (FIB), Micro-milling, & Micro-turning

The FIB sputters material from a workpiece by Gallium ion beam bombardment. An illustration of this sputtering process is shown in **figure 2**. The workpiece (e.g. a ground rod) is mounted to a set of precision stages and is placed in a vacuum chamber underneath the source of Gallium (see **figure 3**). The two translation stages and one rotation stage in the vacuum chamber, make various locations on the work piece available to the beam of Gallium ions. A tunable electric field scans the beam to cover a pre-defined projected area. A high voltage potential causes a source of Gallium ions to accelerate and collide with the work piece. The collisions strip away atoms from the work piece. In the example shown in **figure 2**, the result of the FIB machining process is to create a near vertical facet. Our FIB has either a 200 or 400 nanometer beam diameter, although some FIBs have beam diameters as small as 5 nanometers, making the FIB a true micro-scale capable machine. Sandia National Laboratories has teamed with Louisiana Tech University to further develop the FIB machining technology.

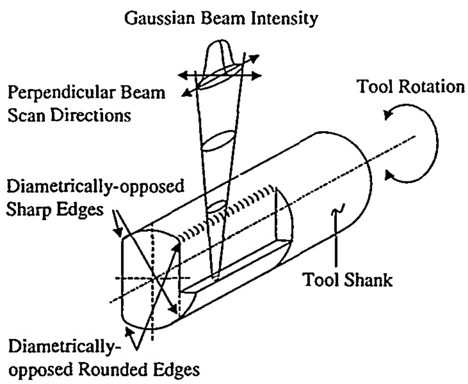

Figure 2: Beam of Gallium ions machining a facet on a cylindrical work piece.

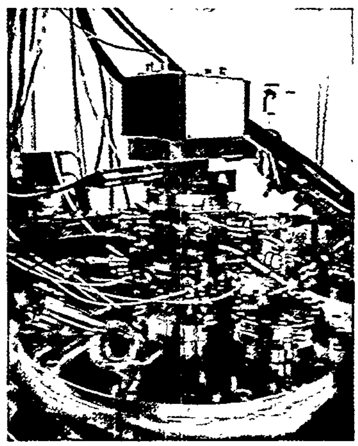

Figure 3: FIB showing source of Gallium sitting over vacuum chamber.

The hexagonal tool shown in **figure 4** was fabricated in the FIB by using the rotational stage to rotate a ground rod to six equally spaced angular positions. This hexagonal tool is similar to the micro-milling tool that was mounted on a high precision milling machine (Boston Digital BostoMatic 18) to machine a channel in aluminum as shown in **figure 5**. The micro-turning tool shown in **figure 6** is another example of tool that can be fabricated in the FIB. This micro-turning tool was used on a lathe to fabricate a finely threaded rod.

The bulk of the FIB effort has been to machine hard tooling instead of directly machining features onto the end work piece. The slow material removal rate has rendered the FIB as impractical for direct machining large features (see **table 1**). The hard tools, however, can remove material at an impressive rate and are durable enough for several hours of machining time (one tool was used for six hours). Nevertheless, the FIB is practical for directly machining complex three dimensional shapes that do not require a substantial material removal rate. The sinusoidal profile shown in **figure 7** was directly machined into silicon by the FIB. Length of exposure and angle of incidence can greatly affect the geometry of directly machined features.

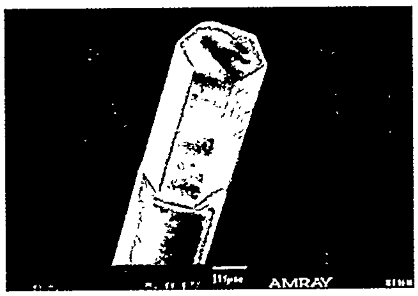

Figure 4: $25\ \mu m$ end mill. (M. Vasile, Louisiana Tech University)

Figure 5: $25\ \mu m$ by $25\ \mu m$ channel machined in Aluminum.

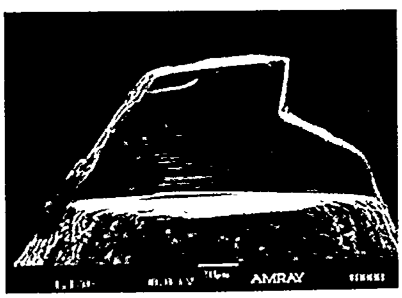

Figure 6: 30 micron width turning tool.

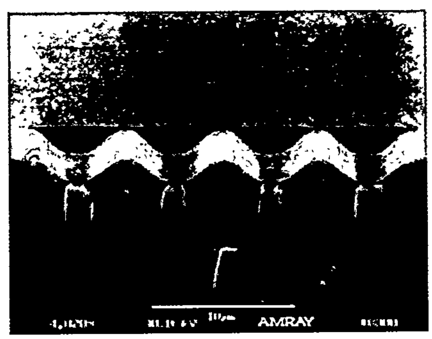

Figure 7: A sine wave directly machined by a FIB. Wavelength = $7\ \mu m$ (M. Vasile, Louisiana Tech University).

<u>Laser machining</u>

Sandia has an excimer laser (Lumonics Hyperex-400, 248nm) set up for meso-scale machining. The excimer laser machines material by pulsing it with nanosecond pulses of ultraviolet light. The work piece is mounted to precision translational stages. A controller coordinates the motion of the work piece relative to the stationary UV laser beam and coordinates the firing of the pulses. **Figure 8** is a schematic of a mask projection technique that can be used to define machining geometries. The mask is inserted into the expanded part of the beam where the laser fluence is too low to ablate the mask. The mask geometry is de-magnified through the lens and projected onto the work piece. This approach can be used to machine multiple holes simultaneously. **Figure 9** is an image of an array of 48 micron holes simultaneously machined into alumina. Sandia's excimer laser has been used to machine polymers, ceramics, glass and metals having feature sizes as small as 12 microns. **Figure 10** is an image of a 25 micron by 25 micron channel machined by the excimer laser into PZT. The vertical walls in the channel are a result of good coupling between the UV wavelength (248 nm) and the PZT material. **Figure 11** is an image of a 12 micron hole machined by the excimer into kovar using the mask projection technique. The debris on the entrance side of the kovar sheet is a result of thermal melting of the material. The mask projection technique has been used successfully with YAG lasers as well, however, re-solidified thermal debris is still problematic (**figure 12c**).

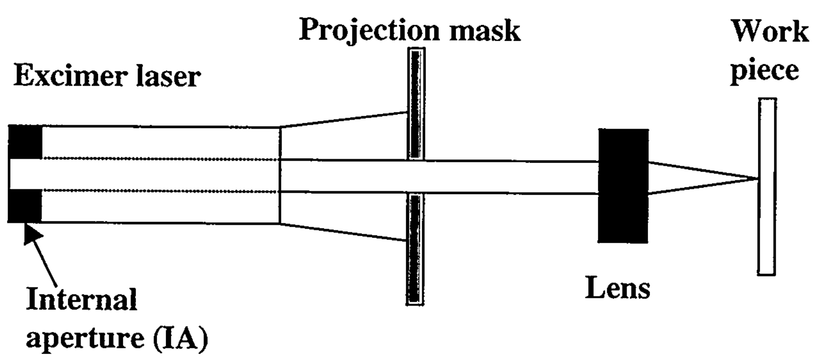

Figure 8: Schematic of excimer laser and mask projection technique.

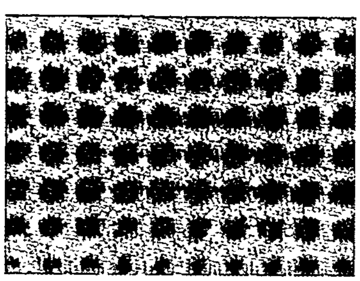

Figure 9: An array of 48 micron holes machined into 275 micron thick alumina using excimer laser mask projection.

Figure 10: 25 µm wide x 25 µm deep trench in PZT using excimer laser.

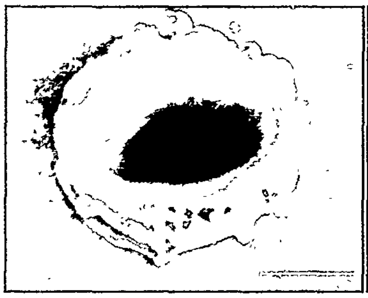

Figure 11: 12 µm dia hole x 25 µm deep in kovar using excimer laser

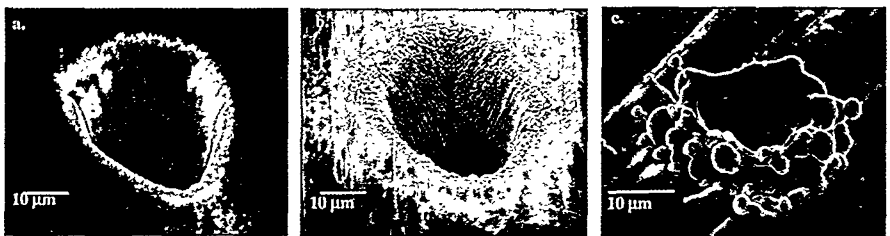

Figure 12: Collaboration with Pulsed Power (SNL): Micro-holes machined in kovar using a Ti:sapphire system (120 femtoseconds) in air (a.) and in vacuum (b.). These are compared with a hole (c.) drilled by a Nd: YAG laser ($\lambda = 1.06$ µm ; pulse width = 100 nanoseconds, P = 50 mW, 2kHz). All images are taken from the entry side of the foil.

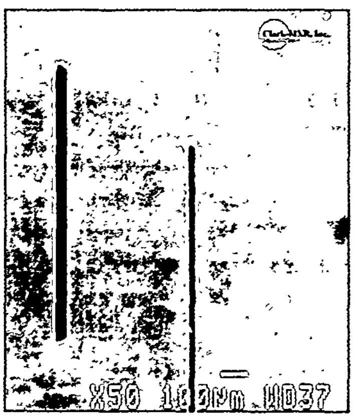

Figure 13: The slit on the left was machined with ultrafast (fs) laser pulses while the slit on the right was machined with long pulses (ns). Material: Invar, 1mm thick. **(Clark MXR Inc.)**

Figure 14: Top view and cross-sectional view of 1 µm dia hole in Silicon . Aspect ratio: 10 to 1. **(University of Nebraska, Center for Electro-Optics)**

A cleaner laser machining approach is to use a Ti-sapphire femtosecond laser (pulse width on the order of 10^{-15} seconds). **Figure 12** shows three images of laser machined holes into identical sheets of kovar, each hole having a similar diameter. The first two holes (a & b) were machined with the Ti sapphire femtosecond laser while the third hole (c) was machined with a YAG laser. The hole shown in **Figure 12a**, which was machined in air, is about as clean as the hole in **figure 12b**, which was machined in a vacuum. The detectable debris that can be observed in images **a & b**, are nano-size particles. These nano-size particles resemble a thin film deposition coating. The minimal debris resulting from femtosecond machining has been observed by Clark MXR and the University of Nebraska (**figures 13 &14**). **Figure 14** is also an illustration of a deep one micron-size feature that can be fabricated using the femtosecond laser. The femtosecond laser ablation process is unique in that it breaks atomic bonds instead of thermally ablating material. The femtosecond laser machining process is appealing for several reasons. It is cleaner, it is micron capable, and it is not material specific.

Micro-EDM (electro-discharge machining)

Electro-discharge machining removes material through a spark erosion process. The micro-EDM machines can machines features as small as 25 microns because the micro-generator needed to create the spark has the necessary fine control for the smaller features. For either the sinker or the wire micro-EDM machine, the two major considerations for determining feature size are the electrode size and the over-burn gap. Sandia has used electrodes as small as 13 microns in diameter and over-burn as little as 3 microns. Currently, Sandia has an Agie Compact 1, micro-sinker EDM machine (see **figure 15**) and will soon possess an Agie Excellence 2F micro-capable wire EDM machine (see **figure 16**). The advantage to the sinker EDM process is that an electrode having a complex three-dimensional geometry can be sunk into a work piece creating the conformal geometry in the work piece. A disadvantage to the sinker EDM is that the electrode also erodes during the EDM process (although at a much slower rate). The advantage to the wire EDM process is that unused wire can be circulated to the work piece during the EDM process thereby presenting to the work piece an electrode having a known geometry. The disadvantage to the wire EDM process is that the feature cuts are of a simple geometry (two and a half dimensional).

Creating an electrode having a complex geometry for the sinker EDM machine is not trivial. Although, graphite is a very desirable electrode material because it machines easily and erodes slowly, copper is also very common. One approach to fabricating a complicated sinker EDM electrode for a meso-scale part is to use the LIGA process. Copper, which is a good performing electrode material, can be plated into LIGA molds. The copper LIGA electrode can then be mounted onto the sinker EDM machine to fabricate a part in a different material such as stainless steel or kovar. This hybrid process is a method of extending the material base for LIGA. **Figure 17** is an image of a small intricate copper electrode fabricated by the LIGA process. This electrode was then used to EDM a .006 inch thick kovar sheet. If the electrode can be described as the bricks then the machined work piece would be the "mortar" that fits between the bricks. **Figures 18 and 19** show the entrance side and the exit side of the kovar part. The most challenging feature on the kovar part is the "mortar" that is .002 inch thick by .006 inch deep (measured into the page).

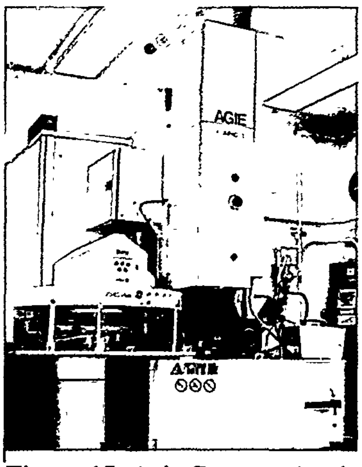

Figure 15: Agie Compact 1, micro-sinker EDM machine.

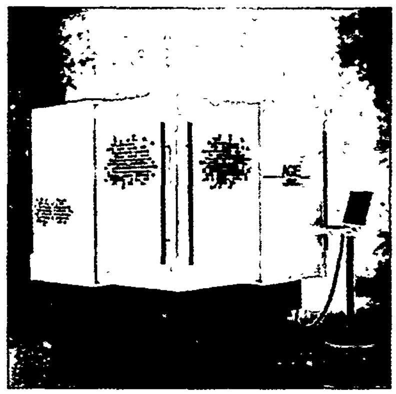

Figure 16: Agie Excellence 2F micro capable wire EDM machine.

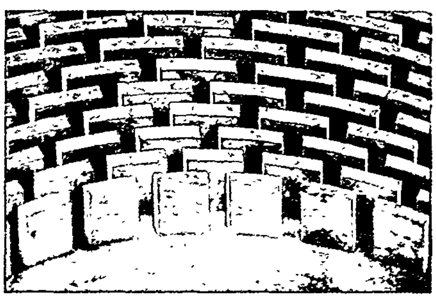

Figure 17: Micro-EDM electrode in copper made with the LIGA process.

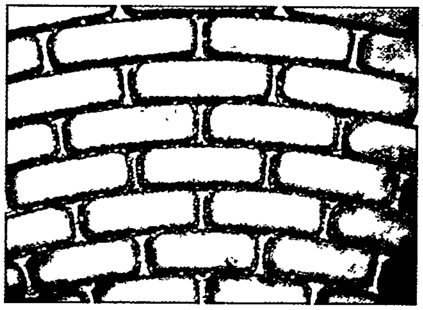

Figure 18: Entrance side of kovar part.

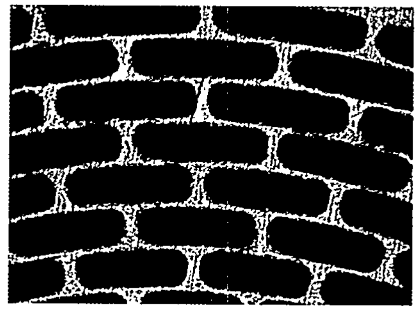

Figure 19: Exit side of kovar part.

SUMMARY OF CAPABILITIES

As in the macro world, no one meso-scale machining process can do it all. Some meso-scale processes are more encompassing than others, but each process has its niche. As in the macro world, designers usually require a variety of materials to optimize performance of mechanical components. For example hermeticity and corrosion resistance may be important characteristics for housing (or packaging) materials but wear and friction characteristics may be important for gears internal to the housing. **Table 1** is an attempt by the authors to summarize meso-scale machining processes. The data in the table is meant to be a representation of the technology but does not represent any particular machine manufacturer. The first column in the table list the technology and also whether the technology can fabricate 3D features or 2D (actually 2.5D) features only. The second column indicates minimum feature size and the tolerance associated with that feature. For example the minimum feature size for micro-milling is 25 microns channel plus or minus 2 microns. The source for the tolerance assigned to micro-milling is a result of the radial run out of the tool when mounted in the collet. The third column lists the feature positional tolerance which is mostly based upon the quality of positional stages used on the machine. In the example of micro-milling, the 25 micron channel can be positioned on the work piece to plus or minus 3 microns. The fourth column lists the material removal rate which is an indicator of how quickly parts can be machined. The FIB has a very poor material removal rate which was a driver for using the FIB to fabricate micro-tools. Although it can take a long time to make a micro-tool, the micro-tool has a high material removal rate and can be used for a significant duration (up to six hours). A feature tolerance and feature positional tolerance of about 3 microns does not compare favorably with LIGA. Nevertheless, a 3 micron profile tolerance on ratchet teeth on a 6 mm diameter part is an equivalent ratio to a .001 inch profile tolerance on a 2 inch diameter part. The point is, 3 microns is probably plenty good enough.

Technology / ***Feature Geometry***	**Minimum feature size /** ***Feature tolerance***	**Feature positional tolerance**	**Material removal rate**	**Materials**
Focused Ion Beam / *2D & 3D*	200 nanometers / *20 nanometers*	100 nanometers	.5 cubic microns/sec	Any
Micro milling or micro turning / *2D or 3D*	25 microns / *2 microns*	3 microns	10,400 cubic microns/sec	PMMA, Aluminum, Brass, mild steel
Excimer laser / *2D or 3D*	6 microns / *submicron*	submicron	40,000 cubic microns/sec	Polymers, ceramics and metals to a lesser degree
Femto-second laser / *2D or 3D*	1 micron / *submicron*	submicron	13,000 cubic microns/sec	Any
Micro-EDM (Sinker or Wire) / *2D or 3D*	25 microns / *3 microns*	3 microns	25 million cubic microns/sec	Conductive materials
LIGA / *2D*	submicron / *0.02um~ 0.5 um*	~0.3um nom. across 3"	N/A	Electroformable: copper, nickel, permalloy (see note)

Note: LIGA can also be used to fabricate parts in polymers, pressed powders, ceramics, and rare-earth magnets with a little degradation in machining performance specifications.

Table 1: Comparison of Meso-scale machining technologies.

MESO-SCALE MACHINING ISSUES

Designers are comfortable with traditional materials (e.g. stainless steel) because these materials have a long history and have been very well characterized through the years. Meso-scale machining processes allow the designer to use traditional materials. On the other hand, tribological issues for meso-scale parts may or may not emulate what is already known. Subtractive meso-scale machining technologies expand the material base and increase the combinations of materials that can come into contact. Galling may be an issue with some material combinations. Each particular meso-scale machining process uniquely affects the surface roughness and morphology. Micro-milling and micro-turning may generate burrs and particles that can cause mechanical interference. Micro-EDM may leave a recast layer that can have particular wear and friction characteristics. Friction effects of meso-scale parts sliding with other parts may have limited points of contact and are not accurately modeled by surface contact models. Some meso-scale machining technologies, such as micro-EDM, are fairly mature, while others, such as femtosecond laser machining, require additional development. Many issues have yet to be identified.

ACKNOWLEDGMENTS

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