

Review of Accomplishments in Abrasive-Waterjet Technology from Macro to Micro Machining -Part 2

H.T. Peter Liu

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Abstract

Abrasive- waterjet (AWJ) technology possesses inherent characteristics unmatched by most machine tools. The initial commercialization of AWJ in the mid-1980s took advantage of its superior cutting power for the raw cutting of thick, difficult-to-machine materials. Subsequently, considerable RD effort was devoted to take full advantage of the above characteristics while refining machining processes toward precision machining and automation. This two-part paper presents the accomplishments that have advanced AWJ technology in terms of improving its cutting accuracy and efficiency, broadening applications for machining delicate materials from macro to micro scales, and enabling 3D capability for multimode machining. In Part 1, six topical areas are presented to demonstrate some of the important achievements in advancing AWJ technology, including control software, meso micro and stack machining, macro to micro machining, cold cutting, hole drilling, and gear making. Seven more topical areas are included in Part 2: biomedical applications, milling and etching, 3D machining, near-net shaping and hybrid machining, special applications, aerospace applications, and field deployment.

Index terms—

1 Introduction

After joining Flow Industries, Inc., where waterjet technology was developed and commercialized, the author had the privilege of participating in R&D activities to advance the technology [1]. He was involved in the commercialization of the technology. Author: Senior Scientist, OMAX Corporation, www.omas.com, November 2020. e-mail: peter.liu@omas.com while witnessing its maturation and growth in the manufacturing community. In the early stages of the commercialization of abrasive-waterjet (AWJ) during the mid-1980s, a reasonable controller to maneuver the operation had yet to be developed. AWJ merely served as a raw cutting tool for difficult and thick materials to take advantage of its superior cutting power. As the technology advanced, additional technological and manufacturing merits were discovered and progressively verified. In addition to the superior cutting power, these merits include environmental friendliness, material independence, cold cutting, adaptability to automation, amenability to micromachining, low loading on work pieces, and 3D capability (Liu and Schubert, 2012; Liu, 2017a). Most of the development efforts in the last three decades, in addition to hardware improvements for improved cutting performance, were to develop controllers and smart software for easier operation and precision machining. Today, AWJ possesses technological and manufacturing merits that are superior to most other tools. It has been elevated as a modern machine tool competing on equal footing among lasers, electrical discharge machining (EDM), and precision milling tools.

AWJ is capable of machining most materials, from metals to nonmetals and anything in between, regardless of conductivity or reflectivity. In particular, AWJ will meet the challenge of machining nanomaterials integrated with various material types possessing nonlinear material properties (Liu, 2017b). The diameter of a water-only-jet (WJ) is defined by the diameter of the jet's orifice. A single-phase WJ with diameters smaller than 100µm has been used to cut relatively soft materials such as fabrics, rubber, foam, thin plastics, and various food products (Yadav and Singh, 2016). With the entrainment of abrasives and air as well as the incorporation of the mixing

tube, the diameter of three-phase AWJ is about three to four times that of WJ. At present, the smallest kerf width achievable with the AWJ is around 300 to 400 μm . Preliminary tests using a research μAWJ nozzle, with a $\phi 0.076$ mm orifice and a $\phi 0.18$ mm mixing tube, have shown that a kerf width of 200 μm is achievable (Liu and Gershenfeld, 2020). Very thin materials that are too delicate to machine otherwise can be machined by stacking A Abstract-Abrasive-waterjet (AWJ) technology possesses inherent characteristics unmatched by most machine tools. The initial commercialization of AWJ in the mid-1980s took advantage of its superior cutting power for the raw cutting of thick, difficult-to-machine materials. Subsequently, considerable R&D effort was devoted to take full advantage of the above characteristics while refining machining processes toward precision machining and automation. This two-part paper presents the accomplishments that have advanced AWJ technology in terms of improving its cutting accuracy and efficiency, broadening applications for machining delicate materials from macro to micro scales, and enabling 3D capability for multimode machining. In Part 1, six topical areas are presented to demonstrate some of the important achievements in advancing AWJ technology, including control software, meso micro and stack machining, macro to micro machining, cold cutting, hole drilling, and gear making. Seven more topical areas are included in Part 2: biomedical applications, milling and etching, 3D machining, near-net shaping and hybrid machining, special applications, aerospace applications, and field deployment. The combined topics clearly demonstrate the technological and manufacturing merits and versatility of AWJ technology, which has been competing on equal footing with subtractive and additive manufacturing tools. With the "7M" advantage together with its green manufacturing properties, AWJ has considerable potential to become an all-in-one and one-in-all machine tool for machining from macro to micro scales. For extremely precise parts made from difficult-to-cut materials, AWJ preferably serves as a neat-net shaping tool that removes the bulk of the material quickly without damaging the parent materials. The parts can then be finished with light trimming using proper precision tools to minimize retooling and/or tool replacement costs while expediting the turnaround time. multiple layers of materials with AWJ. The increase in the thickness of the stack not only stiffens the individual layers for ease of fixturing but also enables the activation of the Tilt-A-Jet for machining nearly taper-free edges 2

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3 II. R&D and Demonstration Facilities

. As a cold-cutting tool without the induction of a heat-affected zone (HAZ), AWJ often is capable of cutting one order of magnitude faster than solid-state lasers (pulsed at high frequencies) and wire EDM (cut with multiple passes) (Liu, 2019a). For extremely precise parts made of difficult materials, end mills and spindles are often subject to severe tool wear resulting in high retooling costs. AWJ can be preferably applied as a near-net shaping tool to remove the bulk of the materials. Near-net-shaped parts can then be finished via light trimming with precision CNC tools. Such a hybrid process would speed up the turnaround time while minimizing the labor and retooling costs.

Future advancement in AWJ technology is expected to develop an all-in-one and one-in-all tool for precision machining from macro to micro scales. Continued efforts are underway to improve the cutting accuracy and to further downsize μAWJ nozzles. In this two-part paper, recent advancements in AWJ technology that take advantage of its technological and manufacturing merits are described. In particular, several established and new trends in applying AWJ for precision machining will be presented, primarily based on the author's R&D and marketing experiences in the field.

OMAX Corporation is equipped with two laboratories for R&D and demonstration. The R&D Lab is dedicated to engineering research and development, including components and processes testing. The Demo Lab is mainly for demonstrating AWJ machining for prospective and existing clients. There are several JetMachining® Centers (JMC) from the four product lines installed in the two laboratories 3 A number of accessories are installed on these machines to enhance AWJ machining . Two of the JMCs used most often for general and meso-micro machining are the OMAX 2652 and MicroMAX. ? Tilt-A-Jet (TAJ) for edge compensation.

. Key accessories include but are not limited to:

? Rotary Axis (RA) for axisymmetric machining ? A-Jet (or articulated jet) for beveling and countersinking. ? Precision Optical Locator (POL) for facilitating alignment and orientation of pre-machined components for precision machining. ? Vacuum Assist (VA) for low-pressure piercing and machining to mitigate nozzle clogging. A combination of multiple accessories are often used to machine certain features. For example, the combined operations of the A-Jet and Rotary Axis can be used to machine rather complicated 3D features such as the "fish mouth" weld joints on pipes.

4 III.

5 Advances in AWJ Technology a) Biomedical applications

The "7M" advantage of waterjet technology, particularly the capability of meso-micro multimode machining of difficult-to-machine materials, has been demonstrated as a potential tool for a wide range of biomedical manufacturing due to the technology's versatility (Liu, 2017b(Liu, , 2012)). Many orthopedics and prosthetics, particularly implants, are made from biocompatible metals such as titanium, stainless steel, Inconel, Nitinol, and other materials that present a challenge to conventional machine tools. Figure 1 illustrates a collection of metal

orthopedic components, including several forms of mini plates for implant fixation. The 5/10 nozzle was used with 320 mesh garnet. The majority of prosthetic and orthopedic components are made of titanium because of its physical qualities: high strength, toughness and durability with low density, corrosion resistance and, most importantly, biological compatibility. On the other hand, stainless steel remains the material of choice for surgical instruments because it is strong, durable, and able to withstand harsh sterilization procedures.

While there are considerable challenges to micromachining titanium with contact tools, AWJs cut titanium quickly and effortlessly (34% faster than machining stainless steel). In addition, the fatigue performance of AWJ-cut titanium could be greatly enhanced (by at least a factor of 3) through the use of a simple secondary process of dry-grit blasting (Liu et al., For machining 3D orthopedics and prosthetics, a Rotary Axis, A-Jet, and/or combination of both can be used. Figure 2 shows AWJ-cut diamond-shaped holes on a stainless steel plate (Figure 2a) and a 6 mm O.D. titanium tube (Figure 2b). The titanium tube featuring the shaped holes is called titanium mesh cage TMC) and is used in spine surgery (Grob et al., 2004). The TMC is a rigid structure that is not amenable to bending about its axis. An alternate design with an interlocking link would have built-in flexibility about and stretch ability along its axis. Such interlocking features can be readily machined with the aid of the Rotary Axis, such as the TMC shown in Figure 2c. Composites such as carbon fibers and ultrahigh molecular weight polyethylene (UHMW) have been used extensively for many years in engineering and aerospace manufacturing to take advantage of their excellent strength-to-weight ratio. They were subsequently adopted for fabricating prosthetics for exterior fixation. Waterjet technology has been applied to machined biomedical components for all these materials (Liu, 2017b). Figure 3 shows two carbon fiber knee braces machined with a waterjet. 2D carbon fiber components were first machined with a waterjet and then thermally formed to their final shapes. For implants and internal fixation components, only few composites are biocompatible and free of contaminants. One such composite is polyether ether ketone (PEEK), which was originally launched by Victrex plc in 1998 and marketed as PEEK-OPTIMMA. Extensive laboratory and clinical tests have shown the superiority of PEEK to metals and UHMW as implant materials (Kurtz and Devine, 2007). The chemical structure of polyaromatic ketones confers stability at high temperatures (exceeding 300°C). Resistance to chemical and radiation damage.

Compatibility with many reinforcing agents (such as glass and carbon fibers). Greater strength (on a per-mass basis) than many metals Compatibility with modern medical imaging techniques (i.e., no shadows in X-ray, CT or MRI images).

AWJ cutting tests of prosthetic and orthopedic components were conducted using PEEK materials supplied by Victrex and Invibio Ltd. Cranial implants, which must be sized to fit individual patients of all ages from infants to adults, are often made with PEEK. Figure ?? shows samples of AWJ-machined PEEK cranial implants with a thickness of 3.2 mm. The samples were machined in 2D and then thermally shaped to become a 3D spherical segment. Such implants can be fabricated in several hours, including the secondary processes necessary to meet FDA requirements. For remote areas where supplies are scarce and timely shipment from manufacturers is not an option, patient-specific implants can be fabricated locally by field-deployable waterjet and portable waterjet systems. 5,6 a. Unfilled b. Filled The surgical clamp consists of several teeth for clipping onto various objects, such as surgical tubes or blood vessels, during surgery. The clamp was cut in three separate steps from left to right, As elaborated in Section III.c.i. It is essential that there is no taper along the entire length of teeth so that the clamp will tightly grip objects. To ensure taper-free teeth and tips, the clamps were machined with the Tilt-A-Jet activated. For laparoscopic surgery using a trocar insertion, blind puncture access procedures are used. This could lead to complications due to over-puncture. When tissue membranes yield under applied stress, the tool can suddenly accelerate forward into the patient. A novel device that actively opposes forward acceleration of the tool was designed and tested (Begg, 2011). One of the critical elements of the device is a delicate flexure. Collaborating with the Precision Engineering Research Group at MIT, OMAX machined several aluminum flexures for constructing the novel device for testing, as illustrated in Figure 6 7

6 b) Milling and Etching

AWJ milling and etching have been niche applications that represent only a small percentage of AWJ machining operations. Since AWJ has considerable cutting power, precise control of the milling depth requires very high nozzle traversing speeds that are beyond the capability of current AWJ platforms. Since current nozzle traverse speeds are low, workpieces are instead mounted on rotating platforms capable of achieving high speeds to perform these operations. The size of the platform is governed by the size of the workpiece. For small workpieces, a small-sized platform rotating at high speeds will suffice; for large workpieces, a large rotating platform is required, as the rotational speed is proportional to $r\omega$, where r and ω are the radius of the platform and rotating speed, respectively. In addition, steel mask was often used to protect the areas that were not to be etched or damaged by stray abrasives (Miles, 1998). The masked milling approach has been successfully applied to a wide variety of structures ranging from 2.4-m diameter space-based optics, turbine engine components, and flow channels in flat heat-exchanger panels (Miles, 1998). Maskless milling would require control of the vector sum of the nozzle traversing speed and the speed of the rotating platform to machine the designed surface profile on the workpiece.

AWJ etching has also been used sparingly because of the complexity in setup and the etching process itself. A new approach was developed, Intelli ETCH, that utilizes a predefined height map. The height map is an image (e.g., a bitmap or jpeg file) that contains brightness levels that correspond to a grayscale ranging from "0" for

black to "255" for white and all of the different shades of gray in between. The brightness values dictate how deep the etching should be at any particular point, with black being the deepest and white being the shallowest etch. The user defines the maximum and minimum speeds while the utility fills in the speeds for each shade of gray that falls in between. From there, the image is analyzed and speeds are assigned to each shade value encountered on the image. A machine may then be configured to modulate the speed at which the position actuator moves the nozzle across the workpiece, with slower speeds provide relatively more etch depth and faster speeds provide relatively less etch depth (Olsen, 2009). The approach enables users to change the speed of etching for a very high-resolution all-in-one process as opposed to handling depth variation with multiple processes and masking.

In this section, examples of AWJ masked milling and AWJ etching are presented. An example of maskless milling is presented in the next section. A novel approach for masked milling for small workpieces is described herein. A dual-disc anemometer (DDA) was developed with the ability to measure water droplet and abrasive speeds 1000 m/s and higher in waterjets and abrasive waterjets (Liu et al., 1998). This capability was enabled by incorporating a low-cost router with a maximum rotating speed of 23,000 rpm to 27,000 rpm. The DDA was subsequently modified for an AWJ milling workstation to take advantage its high rotating speeds, as shown in Figure 7. All the rotating components were enclosed in a protective steel casing as a safety measure. A steel mask on top of a workpiece was mounted just under the cover plate on the end of the shaft of the router. A radial slot was machined on the cover plate along which the AWJ traversed during milling operations. The material removal rate is inversely proportional to the vector sum of the rotating speed of the workpiece and the traverse speed of the AWJ nozzle. For a 10-cm diameter workpiece, for example, the linear speed at a radial position of $r = 5$ cm is nearly 2 m/s. At such a high speed, the material removal rate per AWJ traverse was very low. Materials on the workpieces were removed where the slots were present on the mask. Milling was carried out by installing the modified DDA in one of the AWJ platforms. The router was first turned on until a stable rpm was established followed by traversing the AWJ back and forth along the slot to mill the workpiece. The number of traverses depended on the milling depth and the machinability of the material.

Figure 8 shows a steel mask on which a set of slots was machined. Three workpieces made of Lexan, aluminum, and stainless steel were milled. The rotational speed was set to 10,000 rpm. The MAXJET 5 nozzle with a 0.36 mm/0.76 mm orifice/mixing tube combination, operating at 240 MPa, was used. Milling was conducted using 220 mesh garnet with a mass flow rate of 0.16 kg/min. The radial traverse of the AWJ nozzle was 1.27 m/min. The number of traverses for the aluminum and Lexan runs were 20 and 10, respectively. Based on the depth of these milled surfaces, the rates of the milling depth on the aluminum and Lexan workpieces were measured to be 6.4 microns and 15 microns per traverse, respectively. The above results demonstrate that milling blind micro channels on various substrates with rates of milling depth in the micron or submicron range per revolution can be achieved by using finer abrasives at relatively lower pressures, particularly for materials with relatively low machinability such as stainless steel and titanium. It is interesting to point out that both the mask ribs and the workpiece channels are distorted slightly in the radial direction due to high centrifugal forces. The milled pattern on the workpieces were identical to that on the mask, as expected. Further process optimization could be achieved by adjusting the rotational speed of the DDA based on the geometry of the mask and its material properties to mitigate this observed distortion.

Figure ?? shows the surface profiles of the blind channels on the Lexan (a) and stainless steel (b) parts. The profiles were measured with a COBRA Scanner. The abscissa and ordinate represent the radius from center of the part and the depth of the blind channels, respectively. The average depths of all but the outermost channels were approximately 0.4 and 0.25 mm, respectively. The difference is attributed to the difference in machinability (517 versus 81) although the milling cycles were 10 and 20 for the two parts. The effect of the centrifugal distortion of the parts was evident from the profiles and resulted in very narrow and shallow outermost channels. The material removal rate of AWJ milling was several orders of magnitude higher than that of chemical milling. At the maximum traversing speed of 7.6 m/min, each AWJ traverse over a 0.13 m milling tray takes only 1.2 seconds to complete. At a milling rate of 1 micron per traverse, for instance, it would only take a couple of minutes to mill 100-micron-deep features on multiple workpieces per load for virtually any materials. Chemical milling, on the other hand, would take many hours to complete the same parts-and only for materials amenable to that process. Furthermore, the working fluids used for chemical etching are often toxic, while AWJ is a green manufacturing tool.

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One of the largest and most delicate AWJ milled workpieces, which featured light weighting pockets, was the face sheet of a 2.4 m diameter ULE (ultra-low thermal expansion by Corning) glass mirror (Miles1998). Figure 10 shows the steel mask placed on top of the mirror (a) and the finished part with 9-mm-deep triangular pockets (b). The mask and mirror were mounted on a large rotating platform with a diameter of around 2.5 m. The time required to mill the part was two weeks as opposed to the eight-month estimate for conventional glass machining processing. Since there was no hard tool used to machine this multi-million dollar mirror, the process was considered a safe milling process in comparison with the conventional process. The cost effectiveness, fast turnaround, and process security were the primary reasons that AWJ was chosen for the extremely risky application. AWJ is amenable to 3D machining but must be carried out with discretion. One of the properties of AWJ is that the spent abrasives, if not "tamed" or captured, still possess considerable residual cutting power

that could damage other parts of the workpiece and pose a potential hazard to operators. In other words, AWJ is not inherently suitable for 3D machining by simply mounting the nozzle on a multi-axis manipulator. Although there are such AWJ systems available commercially, their 3D capability is limited because of the difficulty in building Global Journal of Researches in Engineering (A) Volume Xx X Issue III Version I and maneuvering a "perfect" catcher to block the spent abrasives completely, particularly on workpieces with complex 3D features. Because the simplest and most effective means to dissipate the residual energy of spent abrasives is to let the spent abrasives shoot down into a column of still water, most AWJ systems are built on top of a water tank that also serves to support the traversing mechanism. Such AWJ systems that are operating within the limitations of safety are mainly designed for 2D machining ??Olsen, 2012).

Novel approaches have been developed to facilitate AWJ 3D machining while ensuring operational safety by either manipulating the workpiece or incorporating accessories onto the 2D AWJ platform ??Olsen, 2012). Several machining processes have adopted these approaches to broaden the utility of a 2D AWJ platform for 3D machining ??Liu and Olsen, 2013). These processes may be divided into two main categories: those that do require accessories and those that do not. 3D parts may be machined with these processes by manipulating workpiece either during or after the machining process, and by adding accessories to enable 3D machining. Novel multi-axis accessories, for example, the Tilt-A-Jet (TAJ), Rotary Axis, and A-Jet were developed for edge taper compensation, machining axisymmetric features, and machining bevels and countersinks, respectively. 8 , 9 , 10 In addition, a Motorized Z-Axis was made available to follow the contour of non-flat workpieces. 11

8 i. 3D machining without accessories

With the combination of these accessories, complex 3D machining can be carried out on AWJ platforms (Liu, 2019b;2018b).

Examples of 3D AWJ processes that do not require accessories include the assembly of 2D components into 3D parts, secondary processing, cutting parts multiple times, stretching/rearranging 2D parts, AWJ etching and milling, secondary processing, unfolding followed by folding, and layer manufacturing ??Liu and Olsen, 2013).

An example of the assembly of 2D components into 3D parts is illustrated in Figure 12, which shows 3D models of a Boeing 777 and an F-22 fighter jet. Several components of the B777 (wing, nacelle, and stabilizer segments) and all of the F-22 were made from carbon fiber, stainless steel, and aluminum, respectively.

The surgical clamp shown in Figure 5 was machined in three separate steps with the part rotated 90 degrees each step. First, the overall shape was cut (A), then it was trimmed to the specific shape (B) prior to machining the grooves (C). Another example of parts that required multiple cutting steps is another version of a model F-22 fighter jet shown in Figure 13. The prospective, end, side, and top views of the jet and the aluminum block it was cut out of are shown in Figures 13a through d, respectively. The jet was cut in three orientations from a 2 in (5.1 mm) x 2 in (5.1 mm) x 1 in (2.5 mm) aluminum block. There is one tool path that corresponds to each orientation.

First, the block was set up to cut along the axis of the jet (Figure 13b). A home position was established at one of the corners of the block. Cutting began after the nozzle traversed to the established home position. After the first cut, the block was turned 90 degrees counterclockwise to cut along the orientation perpendicular to the jet axis (Figure 13c). After the second cut, the block was turned another 90 degrees to cut on the top of the jet (Figure 13d). After completing the cutting in all orientations, the fighter jet could then be retrieved from the block (Figure 13a). For step-by-step instructions and a demonstration of cutting the fighter jet, refer to the reference video given in the footnote. 12 ii. 3D machining with accessories Accessories that enable 3D machining with AWJ include the Rotary Axis and A-Jet. The Rotary Axis is a water-resistant submersible rotary axis head that allows AWJ to cut axisymmetric features in tubes, pipes, and bar stock. Constant rotational control allows for continuous cutting around a shape. The A-Jet is a software-controlled multi-axis cutting head with a cutting range from 0° to 60° for creating beveled edges, angled sides and countersinks, as well as performing taper compensation. By combining the operation of the Rotary Axis and the A-Jet, the IntelliMAX Software Suite is capable of controlling both accessories to achieve 6axis complex machining of 3D parts with multi-faceted shapes and geometries. Machining operations include Figure 14 shows a chess set made from multiple materials. The chess pieces are aluminum with a copper base for stability and weight. The main checkerboard is aluminum and carbon fiber trim with dark granite and white onyx. Machining was conducted by using the Rotary Axis. The most complicated piece was the knight, which was first modeled in Fusion 360 and then silhouette DXF images were projected as silhouettes at predetermined angles around the whole model. A Rotary and XY movement program was created using these angles and DXF files. Machining was performed at predetermined angles using rotary command and then cut along the associated DXF shadows at those angles. Multiple machining modes, including but not limited to facing, turning, drilling, and etching, were performed in a single operation without removing the part from the Rotary Axis. For modern aircraft engines operating at a very high temperatures, inclined and shaped air-breathing holes must be drilled to achieve efficient and maximum cooling. AWJ was applied successfully to drill such holes on refractory metals with and a without thermal barrier coatings. Figure 15 illustrates these holes drilled with AWJ. By mounting the workpiece on the Rotary Axis, the inclined angles of the holes can be drilled. The geometries of the holes were drilled by controlling the tilting of the A-Jet. Within certain limitations, the inclined angle and shape can vary simultaneously along the hole axis. In the test samples shown in Figure 15, the inclined angles of the holes are fixed. The AWJ nozzle consisted of a 0.18mm

I.D. diamond orifice and a 0.38mm I.D. mixing tube. A 220 mesh garnet with a flow rate of 45 gm/min was used. Seven hole geometries were drilled into these samples to demonstrate the flexibility of the AWJ hole drilling process.

Note that the hole geometries of each column in Figures 15a and 15b are shown in Figure 15c. The actual shapes of the holes were modified as a result of the inclined angle. In Figure 15d, the geometries of the holes drilled on the thermal-barrier-coated (TBC) metal are shown to be different from those drilled in the other two workpieces. Most importantly, there was no delamination between the coatings and substrates and no HAZ on the hole edges in the substrates. The current practice requires a two-step process to drill inclined and shaped holes on TBC metal. First, the nonconductive TBC is removed with a laser. Then, the hole in the substrate is drilled with an EDM process. By combining the operations of the Rotary Axis and A-Jet, 3D parts with complex geometries can be machined. Figure 16 shows several such AWJ-cut steel pipe joints and steel pipe "fish mouth" weld joints that are weld ready. In other cases, the combination of the Rotary Axis and TAJ may be used to compensate for edge taper when machining axisymmetric features.

9 d) Near-net shaping and hybrid machining

There are advanced materials that are very difficult to cut with most machine tools, such as Inconel, titanium, and certain hardened steels. These materials tend to wear out mechanical tools quickly, which leads to very high retooling and tool replacement costs. On the other hand, materials that are prone to heat damage, such as fiber-reinforced composites, must be cut very slowly with thermally based tools such as solidstate lasers and mechanical tools.

The material-independent, cold-cutting AWJ, with its superior cutting power, is most suitable for machining these advanced materials. For most applications, its cut time is typically much faster than that of most thermally based tools. The AWJ-cut parts do not require secondary process such as the timeconsuming and labor-intensive grinding to remove HAZ induced by oxy fuel and plasma cutting. For extremely precise machining operations that exceed the capability of AWJ, it can be used as a first-choice near-net shaping tool to remove the bulk of materials. The netshaped parts can then be finished by light trimming with precision CNC tools. This hybrid process not only minimizes the retooling or tool replacement costs but also shortens turnaround times. Furthermore, trimming also serves to remove the AWJ-induced striation pattern on the cut edges and residual abrasives embedded in the parts. Such a removal process is required for fatigue-critical applications (Liu et al., 2009a).

10 e) Abrasive Slurry Jet

With funding from the National Center for Manufacturing Sciences and the National Science Foundation, a prototype of an abrasive slurry jet (ASJ) was developed by directly pumping a premixed abrasive slurry (Hashish, 1989). The ASJ system was developed for pressures up to 345 MPa and abrasive concentrations of up to 50% by weight. In contrast, the optimum abrasive concentration for the AWJ was about 12% by weight. The abrasive speed in the ASJ when directly pumping the slurry through the orifice reached better than 90% of that of the speed of the waterjet. Conversely, the abrasive speed in an AWJ through the entrainment process was only about 54% to 67% of the speed of the waterjet depending on the abrasive mass flow rate (Liu et al., 1998). The combination of the higher abrasive loading and speed in the ASJ resulted in up to five times the cutting power of AWJ with the same hydraulic power. Furthermore, the abrasives in ASJ can be considerably finer than those used in AWJ, greatly increasing the precision and surface finish of ASJ-milled parts.

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The ASJ prototypes operated in a batch mode with two cartridges of abrasive slurry. After the first cartridge was empty, the second cartridge was loaded while the first cartridge was filled with fresh slurry. The prototypes were equipped with a two-degree-of-freedom robotic manipulator, including a linear traverse to move the ASJ nozzle and a rotating arm to maneuver the workpiece. The rotational axis was a precision air spindle driven by a 5.6hp brushless D.C. servo motor capable of speeds up to 10,000 rpm. For the near-net shaping tests, the ASJ pressure was set between 52 and 69 MPa to slow down the milling process for indepth study.

Milling convex surfaces can be achieved by either ASJ/AWJ turning or milling. For concave surfaces with flat or three-dimensional profiles, only ASJ or AWJ milling can be applied. In principle, the depth of material removal, $h(r)$ where r is the radial distance, is inversely proportional to the vector sum of the traversing speed of the ASJ nozzle and the rotational speed of the workpiece, ω , at the point of impact. Several milling algorithms based on this principle and the motions of the manipulator and the workpiece were designed and tested to shape axisymmetric surfaces on float glass, aluminum nitride (AlN), and other materials. The author developed a milling algorithm applying the ASJ for nearnet shaping of optical lenses on float glass and aluminum nitride (AlN). For each algorithm, a set of ASJ parameters was selected to achieve the required accuracy in the material removal rate according to the operational range of the manipulator. Tests were then conducted to calibrate and verify the algorithms. The algorithm with superior performance was selected for implementation and optimization. The manipulator was programmed to control the rotational speed of the workpiece and the traversing speeds of the ASJ.

A sketch of the algorithm used to mill the concave surface on the AlN workpiece is shown in Figure 17a. This was an example of a maskless milling process as there was no mask where the milling took place. However, a steel mask with a hole of 30 mm in diameter was used primarily to protect the material outside the milled area. In the vicinity $r = 0$, which coincides with the rotational center of the spindle, there is an anomaly of overcutting. The overcutting is the consequence of the vanishing of the rotational speed near the center of rotation. The nozzle was intentionally sped up near $r = 0$ to mitigate the overcutting. As a result, there was a small bump near $r = 0$. The bump was removed by mechanical grinding as described below. Milling was carried out by a multistep process, and optimization was conducted by an iterative process to match the measured and target surface profiles. Because of the hardness of the AlN, a mixture of garnet and aluminum oxide particles with size 320 mesh were used as the abrasive. Corrections of the test parameters governing the depth of material removal were made iteratively to minimize the deviations between the measured and target surface profiles after each step. For a detailed description of the setup and milling process, refer to the original paper (Liu, 1998).

Figures 17b and 17c show the ASJ-milled AlN part with a concave surface and the corresponding surface profiles. In Figure 17c, the target and measured surface profiles for each of the eight steps are represented by colored-coded curves and symbols, respectively. The material removal rate that was accelerated by adding aluminum oxide into the garnet was measured to be approximately 500 μm per step. After each milling step, the surface profile was measured and compared with the target profile. Mechanical grinding was used to flatten the bump near $r = 0$ when the discrepancy between the two was large enough to require correction. The hexagon symbol represents the corrected surface profiles. (Liu, 1998) The surface roughness of the AlN part was measured with a COBRA Scanner. Figure 18a shows a surface profile measured from $r = -10$ to 10 mm, the best-fit 2 nd degree polynomial. The roughness profile of the AlN lens after trend removal is shown in Figure 18b. The surface roughness (R_a) estimated from the profile was 3.4 μm . This was only two to three times that of a mechanically milled surface with R_a ranges from 1 to 1.5 μm . Following the ASJ milling process, the workpiece surface may then be precision ground to optical quality. For comparison, Figure 18c shows the roughness profile on the bottom of the AWJ-milled stainless steel blind channel (Figure 8d). The ASJ-milled surface was considerably smoother than that of the AWJ-milled counterpart as can be observed visually from the two photographs in Figures 8d and 17b. This is resulted from the differences in the pressure, the abrasive size, the vector sum of speeds of the nozzle and rotary platform, and the number of passes of the two processes. Niobium is a very interesting metal. It is naturally hypoallergenic and highly malleable, lightweight, highly resistant to corrosion, and hard. <https://www.thesprucecrafts.com/what-is-niobium-2051218> When it is heated and anodized, it can result in a vast array of iridescent colors. It is often used in a number of medical devices including prosthetics and implants, such as pacemakers. It has been a popular jewelry making materials because of the above properties, particularly the hypoallergenic nature that a safe choice for anyone with metal allergies. Figure 19 shows two sets of earrings and one bracelet made from AWJ-cut niobium metal (Liu, 2017a). The 2/2.5D patterns on the large earrings were formed by laminating two layers of niobium metal with different patterns. The bracelet was first cut out of flat stock with AWJ and then mechanically shaped to the designed form. The spectrum of brilliant color was achieved by anodizing the niobium at different voltages. A stainless steel tube with an O.D. of 12.7 mm served to support the bracelet.

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The strength and durability of carbon fiber has been taken advantage of for fabricating musical instruments that are traditionally made from wood. Carbon fiber holds up a lot better than wood against all sorts of environmental conditions such as changes in temperature and humidity and the beating musical instruments take on the road. According to mezzo-forte, the sound of carbon fiber violin and cellos can be designed to produce a rich, warm, and brilliant sound that rivals even the most expensive Stradivarius. Many of the carbon fiber stringed instruments are often handmade. 14 Semi automating the fabrication process with AWJ can substantially reduce the manufacturing costs of instruments like these. Figure 20 shows an assembled AWJ-machined ukulele made of carbon fiber sheets, wood, steel strings, and stainless steel (Liu, 2017a). For violins or violas, the AWJ-machined front faces can be formed precisely to their curved shape with a post-thermal-pressing process (Liu et al., 2018b). Known as a strong and brittle material, glass has a variety of applications across virtually all industries, including the creative sector. When illuminated by various light sources, the transparent/ translucent properties of glass, together with a spectrum of rich colors, enable the creation of brilliant displays. And for artistic purposes, AWJ technology is ideal for generating glass works of art. Capable of working at a 14 <https://www.rockwestcomposites.com/blog/carbon-fibermusical-instruments-are-they-really-just-as-good/> variety of scales, the AWJ process remains the same with slight adjustments made depending on the delicacy, intricacy and complexity of the design (Cutler, 2012).

Figure 21 shows two examples of art created by assembling multiple layers of AWJ-machined glass pieces. The design process for this type of art can begin in a variety of different ways, such as importing a vector file from any software capable of saving a drawing as a vector file (e.g., Rhino, AutoCAD, Illustrator and Solid Works). As a 2D cutting process, only a single outline is required. The initial programming was performed using various software packages and loaded into the machine's software prior to cutting. The files were made and saved in a

vector format such as a DWG or DXF file. Performing precision cutting of multiple glass layers with conventional tools would be much more challenging, as thin glass pieces are prone to breakage during cutting and handling.

14 g) Aerospace Applications

As a versatile tool with the "7M" advantage together with its superior cutting power, cost effectiveness, and the absence of HAZ, AWJ has been a popular tool for machining various aerospace metals and composites.

i. Aerospace metals AWJ cutting inherently induces striation patterns that may initiate fatigue and premature micro cracking under repeated high cyclical loading. Consequently, AWJ-cut metal parts intended for use in aerospace structural applications must go through subsequent conventional machining processes to meet the Class 1 requirements for fatigue-critical applications. Even for the fatigue non-critical parts (Classes 2 through 4), the default is Class 1 due to the aerospace industry's inherent conservatism.

Requiring secondary processes for AWJmachined parts negatively impacts the cost effectiveness of waterjet technology. Some cost savings may be realized if it can be shown that AWJ net-cut parts have comparable durability properties as conventionally machined parts. Recognizing the tremendous cost advantages made possible by AWJ machining and the significant advancements in waterjet technology for precision machining, OMAX launched an R&D plan in collaboration with Boeing to investigate the fatigue characteristics of AWJ-machined aluminum and titanium. "Dog-bone" specimens were prepared for independent fatigue tests at Boeing and Pacific Northwest National Laboratory (PNNL) (Liu et al., 2009a(Liu et al., , 2009b(Liu et al., , 2010)).

As a part of the test matrix, OMAX prepared three sets of dog-bone specimens made of aluminum alloys (2024-T3 and 7075-T6) and annealed titanium alloys (6Al-4V). Boeing provided all the test materials. The geometry of the dog-bone specimen together with a typical AWJ-cut sample is illustrated in Figure 22. Conventional milling and AWJ were used to machine the dog-bone specimens. Five samples of each material were cut and four were tested to improve the statistical significance of the test results. Milling with R a better than 1.6µm was conducted at Boeing. The milled specimens served as the reference for the AWJ-machined specimens. The AWJ machining was conducted using two nozzles with ratios of orifice and mixing diameters in mm (orifice/mixing tube) 0.36/0.76 (MiniJet) and 0.25/0.53 (MAXJET5), respectively. The garnet abrasive sizes ranged from 80 mesh to 320 mesh. For each nozzle, the specimens were cut for five quality levels: Q1, Q2, Q3, Q4, and Q5. A secondary dry-grit blasting process using 180 mesh aluminum oxide as the media was applied to some of the AWJ-cut specimens to investigate whether the fatigue performance can be improved by smoothing and/or removing the striation pattern. Table ?? presents the naming convention and a description of the specimens. Selected dog-bone specimens were fatigue tested in the Fatigue and Fracture Laboratory at Pacific Northwest National Laboratory (PNNL). 15 For this test, the specimen was gripped at its two ends and cyclic loading was applied until it failed. 16 15 Sanding was conducted at Boeing 16 Dry-grit blasting was conducted at Boeing The number of cycles at which the specimen fails at the gage area is defined as the fatigue life of that specimen, N_{max} . However, the number of cycles is lower than the N_{max} if the failure takes place outside of the gage area. For this investigation, the fatigue tests were stopped when the test cycle reached the run-out conditions without failure, which were defined as 1 and 2 million cycles for the aluminum and titanium specimens, respectively. In those cases, N_{max} was greater than the measured life cycle. The test system used in this study was an MTS 50 Kip servo hydraulic test frame (MTS model 312.31) that was controlled with an Instron 8800 digital controller. The load cell was an MTS 25 metric ton model 661.23A.01. The wedge action grip was an MTS model 647 controlled with an MTS model 585.60 grip supply.

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Specific test parameters appropriate for the aluminum and titanium specimens were chosen according to Boeing's recommendations (Liu et al., 2009a). Fatigue testing was performed in accordance with ASTM standards E466-96 and E468-90. Specimens were prepared per section 5.2.2.2 of E466, providing a continuous radius between ends of a rectangular cross section. These parameters were in specified guidelines in applicable ASTM standards and required a maximum axial stress limit of 207 MPa for aluminum and 483 MPa for titanium at the reduced gage section.

The stress ratios were specified for all tests in the form of a ratio of minimum to maximum stress that cycled between full tension and slight compression. All fatigue testing was performed at ambient room temperature using constant amplitude loading. Standard lab practices were used for testing all fatigue specimens. Alignment of each test specimen was set and checked using mechanical stops against the hydraulic grips. Grip pressure was set to 19.3 MPa (2.8 ksi). Limits were set on the digital controller to protect the sample during loading and to detect fractures in the sample. The constant amplitude sine wave was observed on an oscilloscope during testing as a secondary verification of the load values that were set and displayed on the digital controller. The load cell in the test frame was verified prior to testing and post testing against a calibrated load cell.

Figure 23 shows one of the four specimens tested for the 2024-T3 aluminum dog-bone set. The specimen IDs are (a) 2OMS125-1(baseline), (b) 2O AQ1220-1, (c) 2O AQ3220-3, (d) 2O AQ5220-5, and (e) 2O AQ5220G-1 (grit blasted). The number of cycles at failure, N_{max} , was marked and has been highlighted in red rectangles on each sample. It is evident that N_{max} increases with the quality level of the AWJ-cut samples, although this varied within a range for each of the four samples tested. The N_{max} for the milled sample (a) and the AWJ-cut

sample at Q5 (d) was considered to the same within the experimental error. Q5 represents the highest quality AWJ surface. Notably, the grit-blasted AWJ-cut sample failed at 1,047,468 cycles at the grip but not the gage. This meant that the grit blasting increased the tensile strength of the gage area. In other words, N max would have exceeded that number provided the grip had not failed. Figure 24 shows the test results of the titanium specimens. The test procedure was the same except that the maximum axial stress limit was set from 207 MPa to 483 MPa to take the greater tensile strength of the material into consideration. The specimen IDs were the same as those in Figure 23 with the first two characters changed from "2O" to "Ti". Again, higher quality AWJ-cut samples were observed to have higher N max results. However, N max for the milled samples was considerably higher than that of the AWJ-cut counterpart at Q5. Again, the grip of the grit-blasted AWJ-cut specimen failed at 2 million cycles. Therefore, the expected N max for the titanium sample would exceed 2 million cycles. The measured fatigue life cycle of the aluminum and titanium specimens were plotted against the R a of the cut edges to compare the performance of the milled and AWJ-cut dog bone samples in Figures 25 and 26, respectively. It should be pointed out that the fatigue life cycle in the figures is not the same as the N max for those samples that did not fail at the gage area. For those cases, the fatigue life cycle would be lower than the N max , and significantly lower in certain cases. In these figures, the error bars represent the spread of the measured fatigue life cycle for the four samples tested. For those samples with life cycles that reached the runout conditions (1 and 2 million for the aluminum and titanium specimens, respectively), a question mark indicates that N max is greater than the run-out cycles. In both figures, the fatigue life cycle decreased with the increase in the R a , which is inversely proportionally to the edge quality levels of the AWJ-cut sample. The fatigue life cycle of the milled (base-line) specimen was higher than that of the AWJ-cut counterpart without grit blasting (Figure 23). With grit blasting, the fatigue life cycle of the AWJ-cut sample was at least 2.5 times higher than that of the milled counterpart for aluminum and in the same range for titanium (Figure 24). However, more grit-blasted AWJcut titanium samples reached the specified run-out conditions than the milled samples.

The presence of AWJ-induced striation patterns on the cut edge can initiate microcracking under high cyclical loading. The microcracks grow progressively under loading and lead to premature fatigue failure. Removing this striation pattern was one of the reasons that AWJ-cut metal parts for fatigue-critical applications had to undergo secondary machining with conventional tools. One of the primary reasons that grit blasting improved the fatigue performance was that the process smoothed the AWJ-cut edge and reduced the R a . The extraordinary boost in the fatigue performance could also be attributed to the induction of residual compressive stresses through dry grit blasting. The ability to induce residual compressive stresses has been observed in related processes of "waterjet peening", "abrasive-waterjet peening", and "shot peening" ?? Selected 2024-T3 specimens were sent to the xray diffraction facility at the NIST Center for Neutron Research to measure the residual compressive stresses at the gage (Liu et al., 2009b). Figure 27 illustrates the test results. The abscissa and ordinate are the surface roughness and residual compressive stresses, respectively. The error bars correspond to one standard deviation. The results show that the residual compressive stresses induced by conventional machining are the minimum for all specimens. The average residual compressive stresses induced by drygrit and AWJ blasting processes are nearly 4 times those induced by conventional machining. These results correlate well with the increase in the fatigue life of the specimens machined with the combined process of AWJ and grit blasting, as illustrated in Figures 23 and 24. It is interesting to point out that, although the compressive stresses of AWJ as-cut specimens were higher, their fatigue lives were shorter than that of the baseline case, as shown in Figures 25 and 26. It is evident that R a generally dominates residual compressive stresses. Induced compressive stresses become effective in enhancing fatigue performance only when their magnitudes are comparable to or larger than that of the loading of fatigue tests, particularly for specimens with small R a such as the AWJ-and gritblasted samples. ii. Aerospace composites Aircraft composites have experienced near exponential growth in use in recent years ?? Slayton and Spinardi, 2015). Commercial aircraft manufactures are facing the challenges of producing more lightweight components that help airline operators meet environmental targets while coping with some severe production ramp-up rates. Because AWJ piecing damage can be mitigated by using Turbo Piercer and Mini Piercer (Section IIIe, Part 1 of the paper) on composites and laminates, and drill-head accessories can provide even more reliable drilling for delicate materials, waterjet is now considered the most efficient, consistent and affordable process for cutting composite materials. It provides a superior cut edge surface finish while imparting virtually no adverse impacts or the introduction of fiber pull out, delamination, localized part heating or mechanical stress. Furthermore, AWJ can preserve the parent material's structural integrity to a degree that is simply unmatched by mechanical routing. Abrasive waterjetting has been applied to machine a variety of aircraft composite aero structures, including stringers (trimming), airframes, honeycomb floorboards, wing skins, fuselages, flaperons, rudders, and more (Hashish, 2013).

One example of the successful application of AWJ involved machining honeycomb composites at a low cost for use in the High-Speed Civil Transport (HSCT) aircraft under development at NASA in the 1990s (Hibbard et al., 2000; Liu, 2006). Figure 28 shows two pieces of Boeing honeycomb floorboards (with Nomex cores and fiberglass face sheets) cut with a conventional router and the AWJ (single pass at 5.1 m/min). Figure 28a reveals that there were numerous tears on the jet exit surface of the face sheet cut with the router while no tearing occurred at all on the face sheet cut with the AWJ. Severe tearing of the core materials was also evident on the edge of the floorboard cut with the router, whereas the edge of the floor board cut with the AWJ was clean with no tearing, as seen in Figure 28b.

a. Top view of AWJ exit surface b. Side view Extensive AWJ machining of popular aircraft composites such as carbon fiber, PEEK, G10 (fiberglass-epoxy laminate), and TBC (on turbine engines) has been conducted for various applications. Test results have also served to determine whether the cut quality and accuracy of these materials met the aircraft manufacturers' requirements (e.g., BAC 5578). In Figures 2, 10, and 18, AWJ-cut carbon fiber was used to fabricate the knee brace, model B777, and ukulele to take advantage of its superior material strength, high stiffness, and light weight. PEEK was another relatively new material that was widely used in engineering, biomedical (Figure 3), and electronic applications for its inertness and tolerance for high temperatures.

16 h) Field Deployment

The versatility of AWJ has also been taken advantage of in the context of field deployment. One of OMAX's Mobile JetMachining® Centers, a portable system designed for field deployment, was deployed for rapid response repair at Camp Leatherneck in Helmand Province, Afghanistan, as shown in Figure 29. 17 to fabricate parts in-theater, often fewer than 10 miles from where they would be used. This style of in-field capability is expected to expand beyond the military, such as insitu deployment of the mobile AWJ system for reconstruction efforts following natural disasters in remote locations without access to machining facilities.

IV.

17 Summary

In Part 2 of this paper, the review of the accomplishments in abrasive-waterjet technology development continued to describe a wide range of applications that further demonstrate the versatility of waterjet technology.

Seven sections included applications from biomedical, milling and etching, 3D machining, near-net shaping, jewelry and musical instruments, aerospace, and field deployment. Based on both parts of the paper, the breadth of AWJ applications ranging from macro to micro scales is clearly evident. Several of these applications are unique to AWJ, as they would be considerably challenging to accomplish through the use of conventional machining. https://www.omax.com/sites/default/files/documents/600140a_-_usmc_mobile_jmc_case_study.pdf There is considerable room for AWJ to capture additional market share in the manufacturing sector as a whole. One promising case is applying AWJ as a nearnet shaping tool for extremely precise machining of difficult-to-cut materials, as described in Section III.d. AWJ is capable of removing the bulk of the materials quickly, which means that near-net-shaped parts can then be finished by light trimming with proper precision tools. As such, the hybrid machining process greatly extends the operating life of precision tools and removes any concerns about embedded abrasives in the workpiece. Mitigating abrasive embedment is especially essential for fatigue-critical aerospace structures and the sterilization of orthopedics and prosthetics.

In addition to the "7M" advantage, AWJ is also a green machining tool as it uses no toxic cutting fluids and the water and garnet abrasives are recyclable (Liu, 2018). AWJ has the potential to replace conventional tools that use metalworking fluids (MWFs) during machining and grinding operations for superior cooling, reduced friction, higher workpiece surface integrity, minimized tool wear, and increased productivity increases. Health problems have been reported among workers exposed to MWFs, including incidences of respiratory, digestive and skin cancers (Malloy et al., 2007). For example, one common component in MWFs, chlorinated paraffin (CP), has prompted serious concerns among environmentalists, and the Canadian Environmental Protection Agency (CEPA) has declared all CPs toxic while the US EPA has restricted their usage in manufacturing. 18 Other forms of machining, such as chemical and plasma etching and electrochemical machining, either use toxic working fluids and/or produce hazardous waste. 19 This work was supported by an internal R&D fund from OMAX Corporation. Many sample parts presented in both parts of the paper were machined directly and/or with the assistance from Associates, ChanSuey and Ruvim Mironyuk (ex-Associate), operating OMAX's Demonstration Laboratory. The MicroMAX was developed and commercialized for In an attempt to reduce the use of equipment that may be harmful to the environment, AWJ has been increasingly adopted by the manufacturing community. During the 2018 ASETS Defense Workshop, for instance, a recommendation was made to adopt AWJ in Department of Defense R&D, manufacturing, and maintenance facilities for compliance (Campo, et al., 2018).

¹The author, who began his employment with Flow Industries in 1973, had the honor to be supervised by the late Dr. John Olsen, who enabled the commercialization of waterjet technology by perfecting the ultra-high pressure intensifier pump.

²The TAJ is ineffective for machining thin materials, as the cutting speed is too high for the TAJ to respond rapidly to compensate for the edge taper, however small. 3 <https://www.omax.com/products>.4 <https://www.omax.com/accessories>.

³<http://sme.org/MEMagazine/Article.aspx?id=78461> 6 <https://www.protomax.com/>

⁴<http://pergatory.mit.edu>

⁵© 2020 Global Journals

⁶<https://www.omax.com/accessories/tilt-a-jet> 9 <https://www.omax.com/accessories/rotary-axis> 10 <https://www.omax.com/accessories/a-jet> 11 <https://www.omax.com/accessories/motorized-z-axis>

⁷<https://www.youtube.com/watch?v=GCH2BSfLJ70>

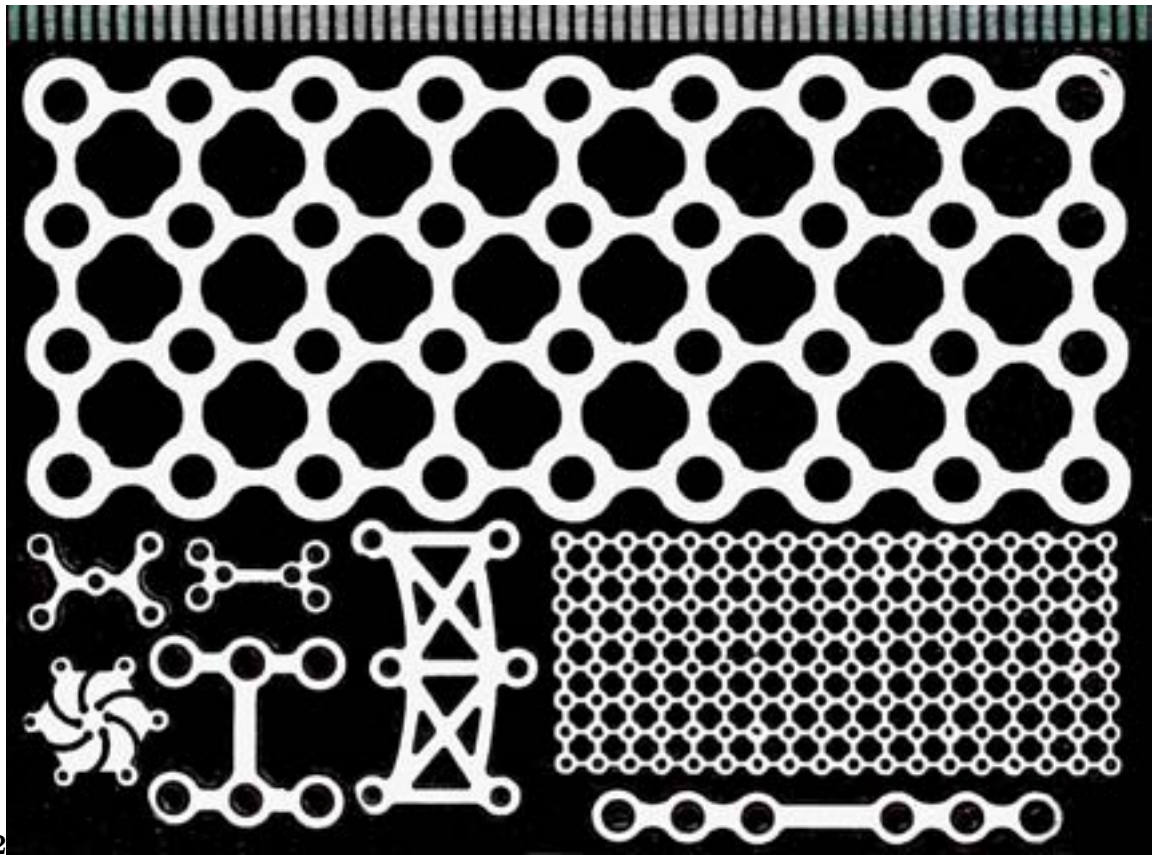


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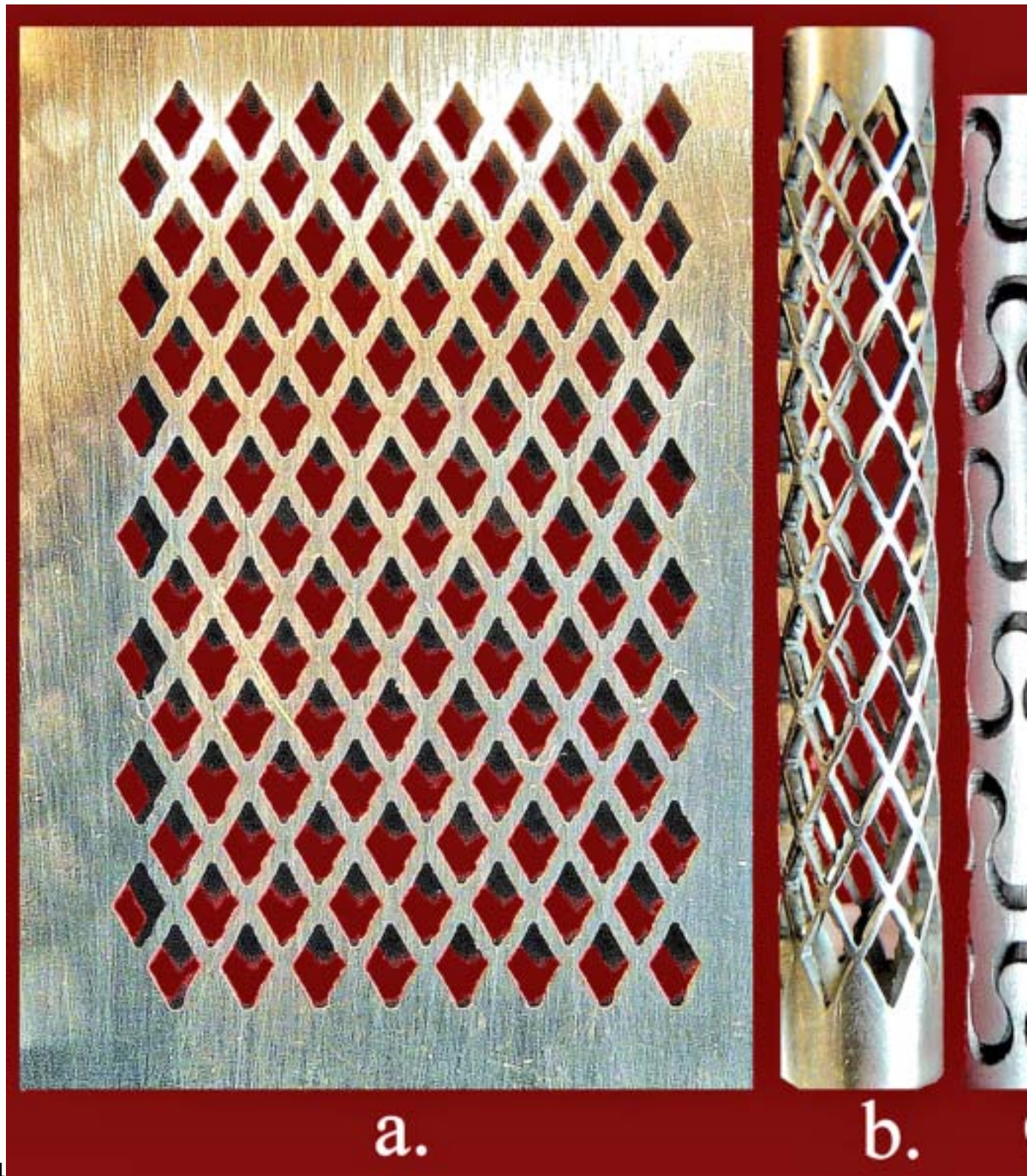


Figure 2: Figure 1 :

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Figure 3: Figure 2 :

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Figure 4: Figure 3 :

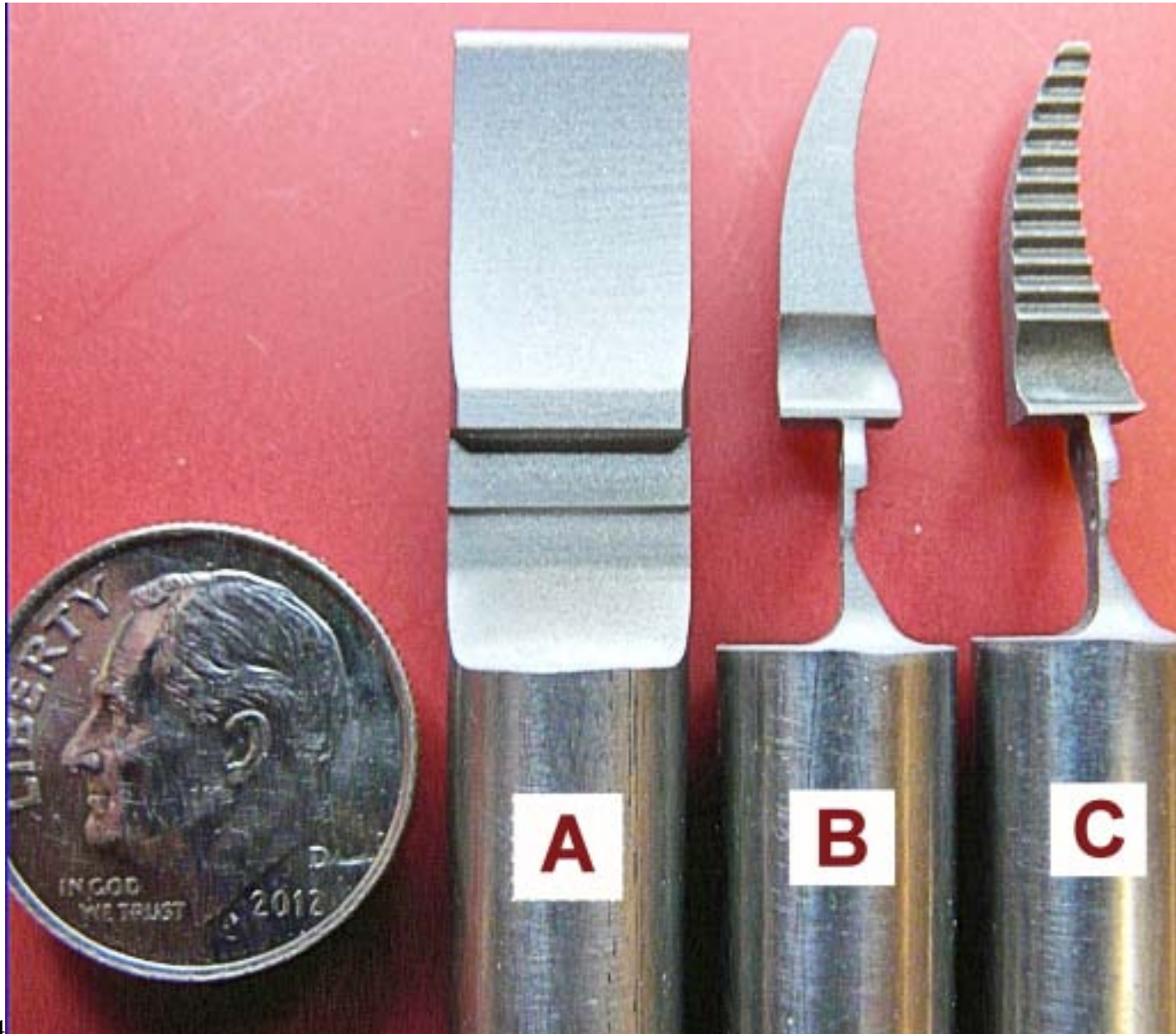


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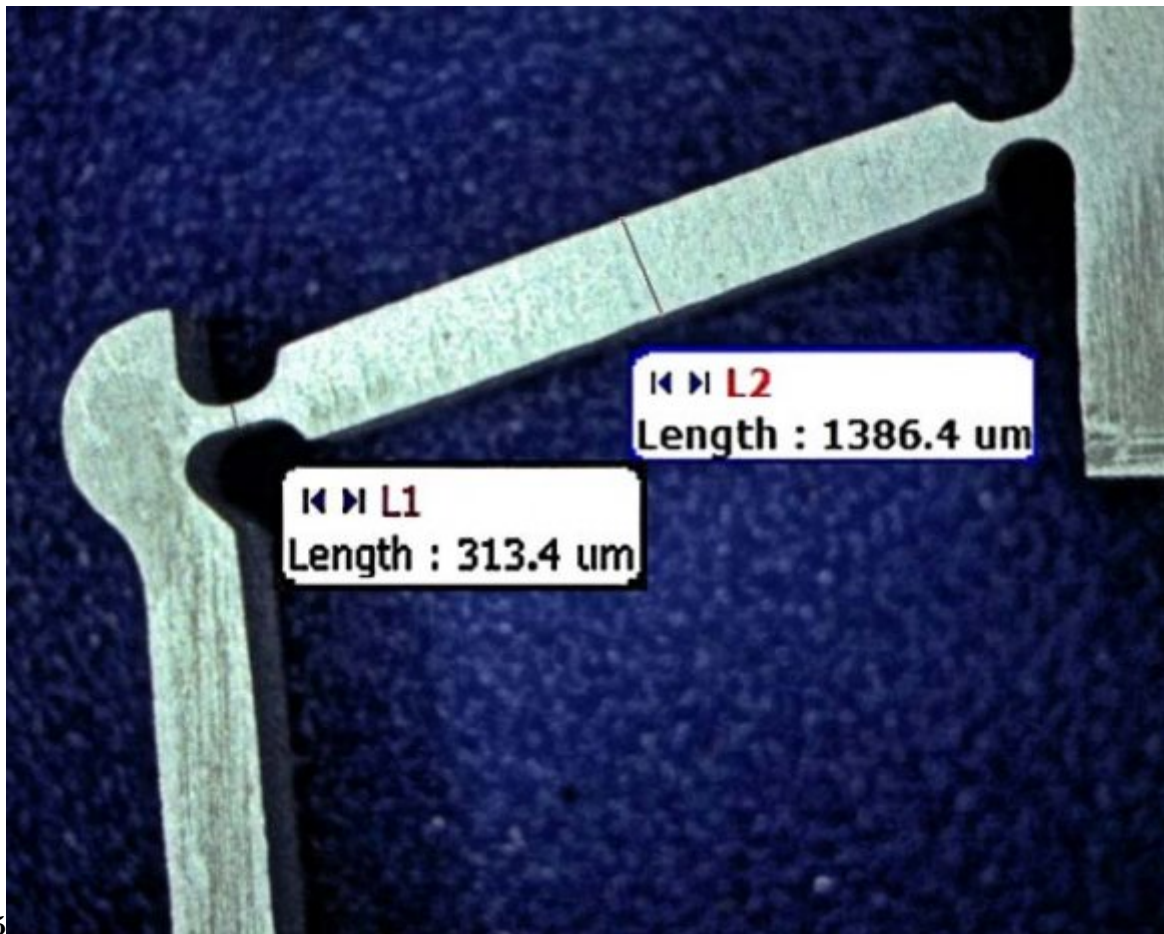


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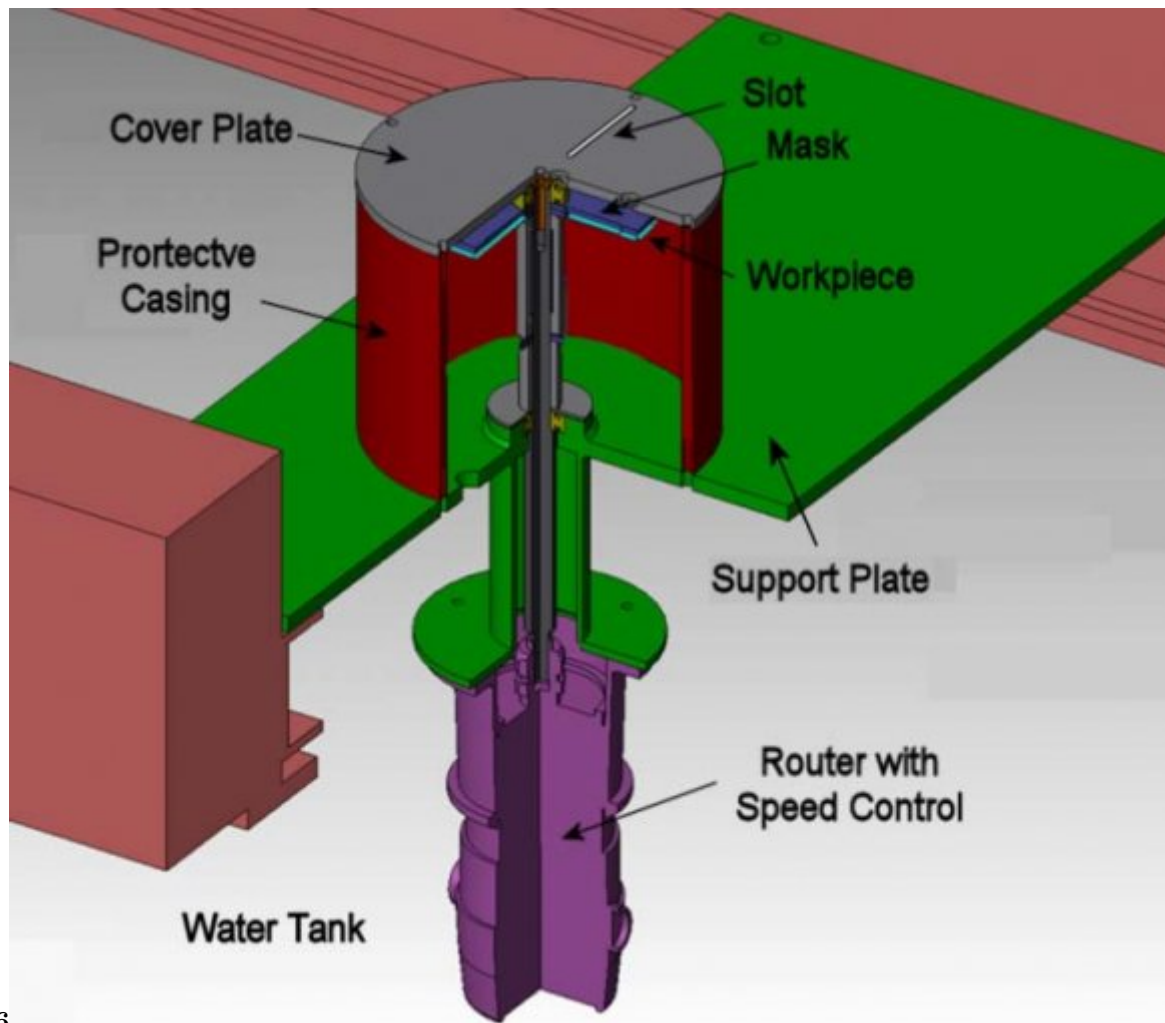


Figure 7: Figure 6 :



Figure 8: Figure 7 :

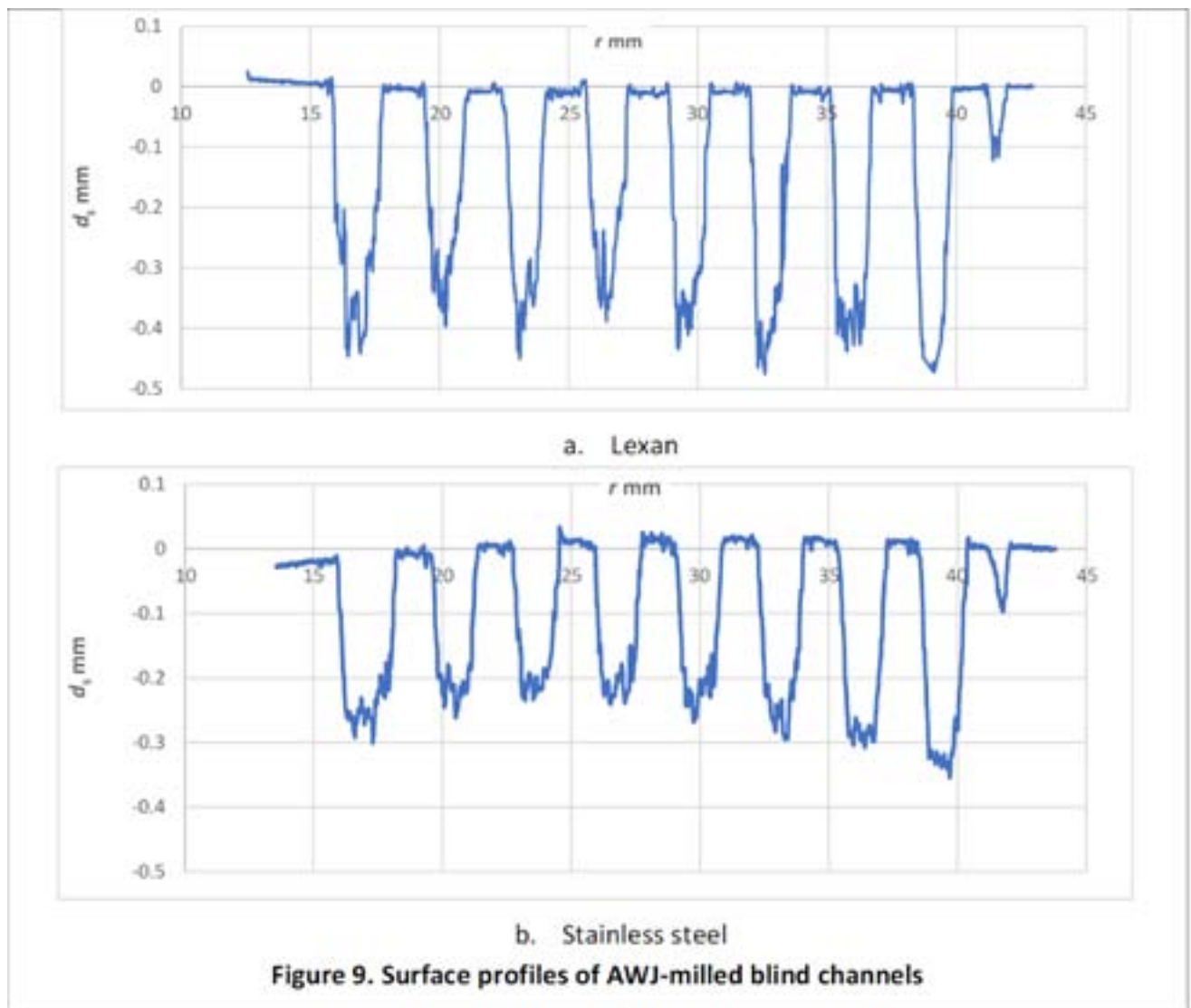
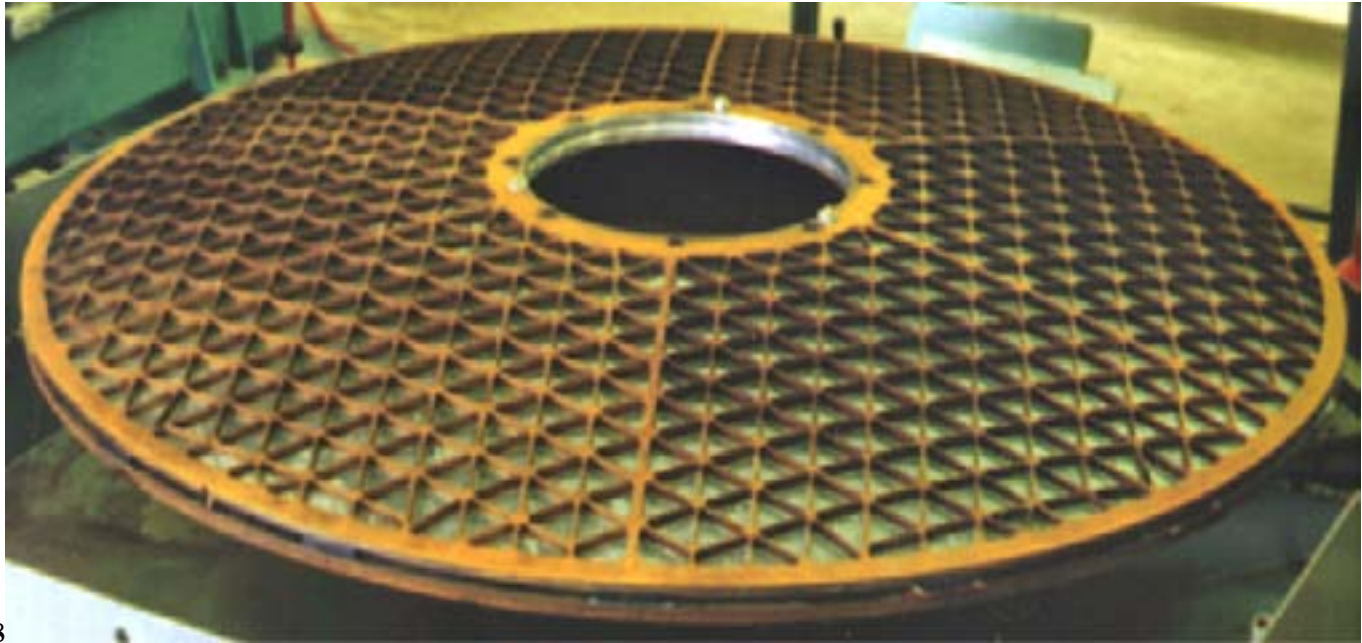
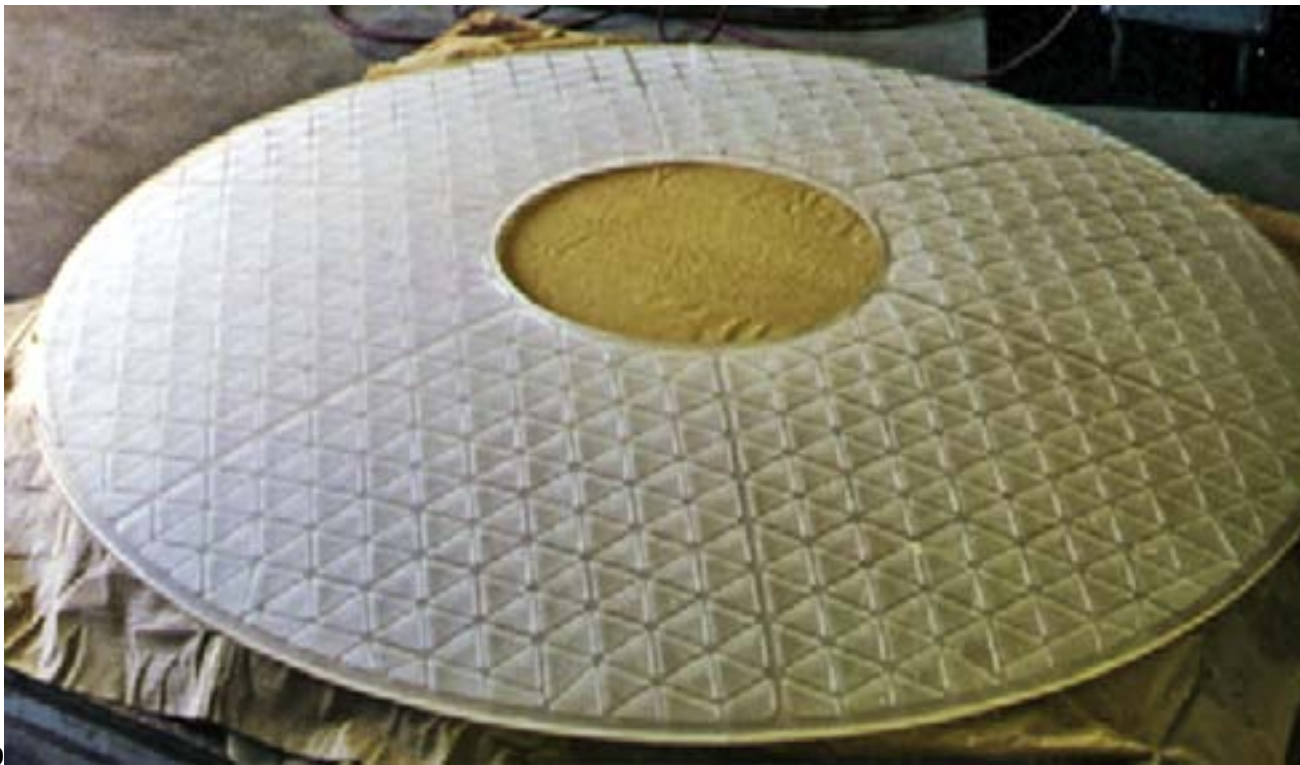


Figure 9:



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Figure 10: Figure 8 :



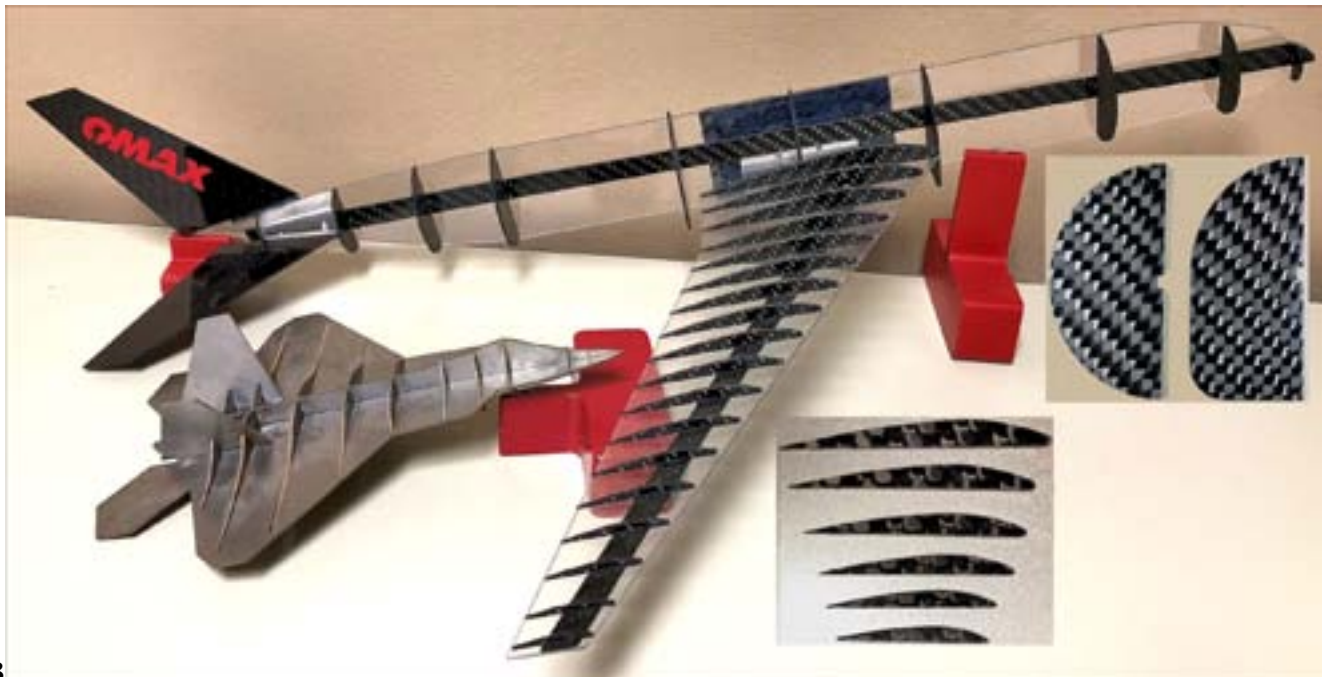
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Figure 11: 6 2020 Figure 9 :



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Figure 12: Figure 10 :Figure 11 :



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Figure 13: Figure 12 :Figure 13 :

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Figure 14: Figure 14 :

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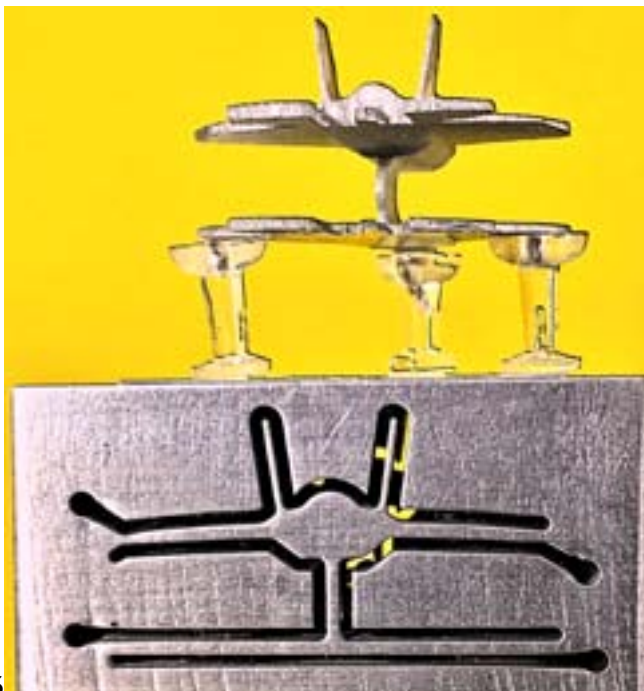


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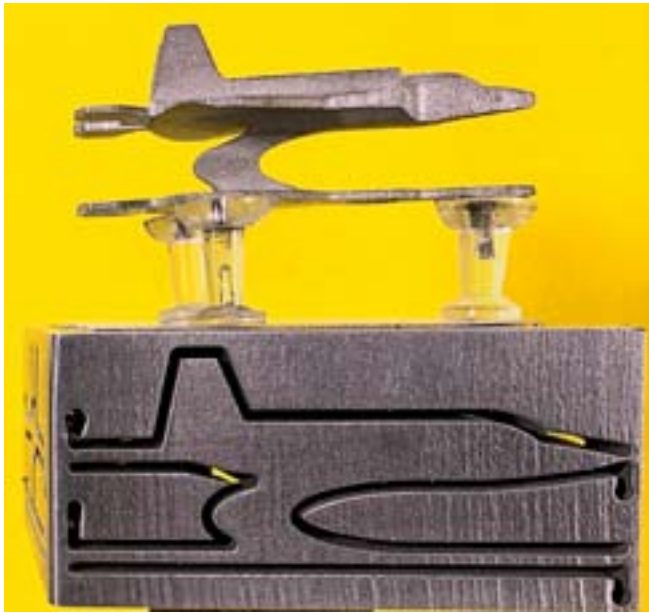
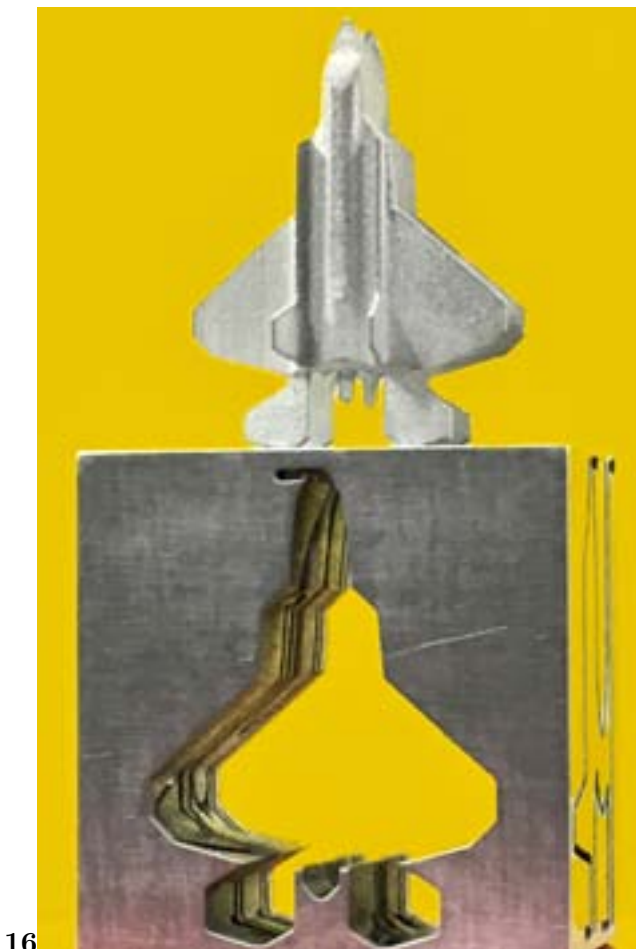


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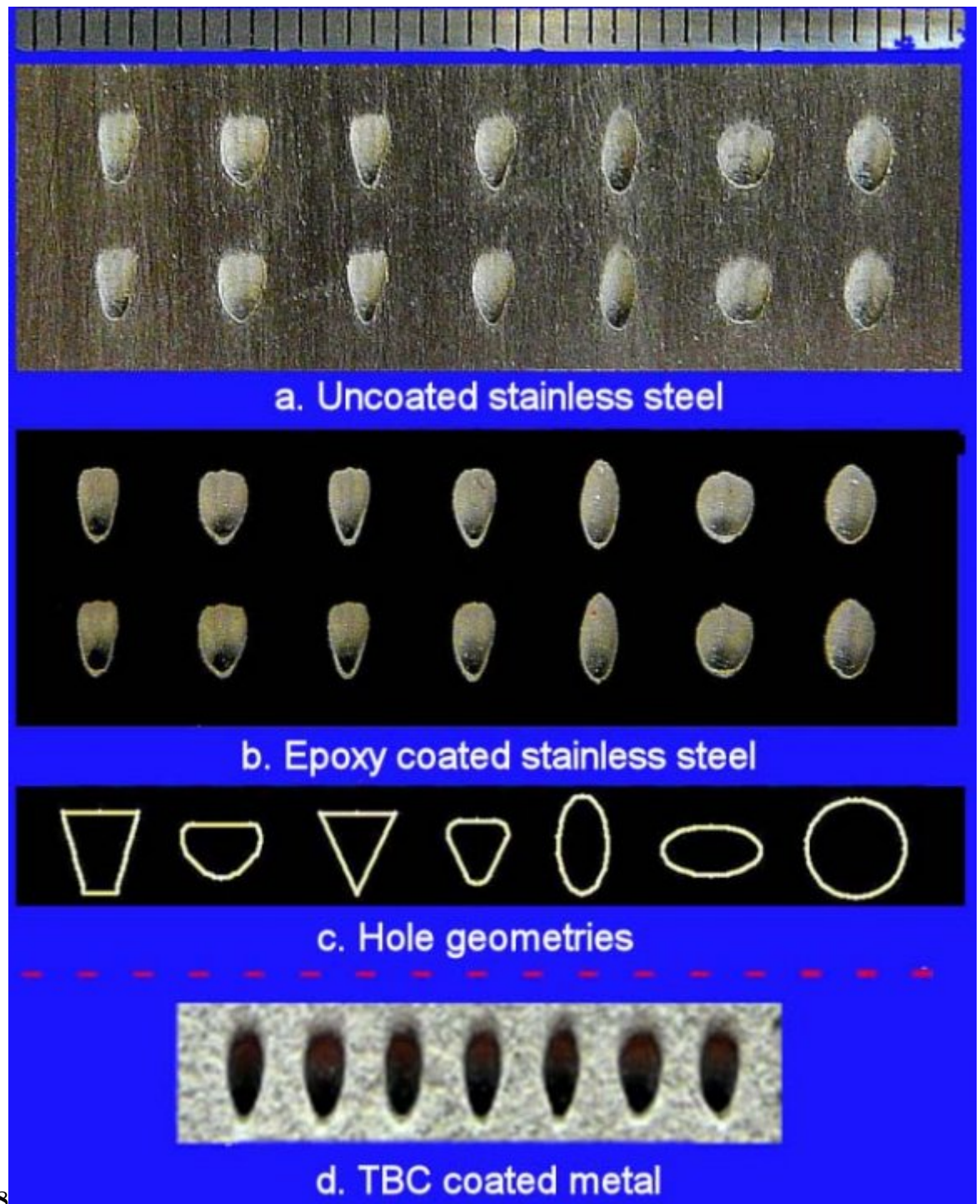
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Figure 17: Figure 16 :

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Figure 18: Figure 17 :



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Figure 19: 12 2020 Figure 18 :



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Figure 20: Figure 20 :

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Figure 21: Figure 19 :

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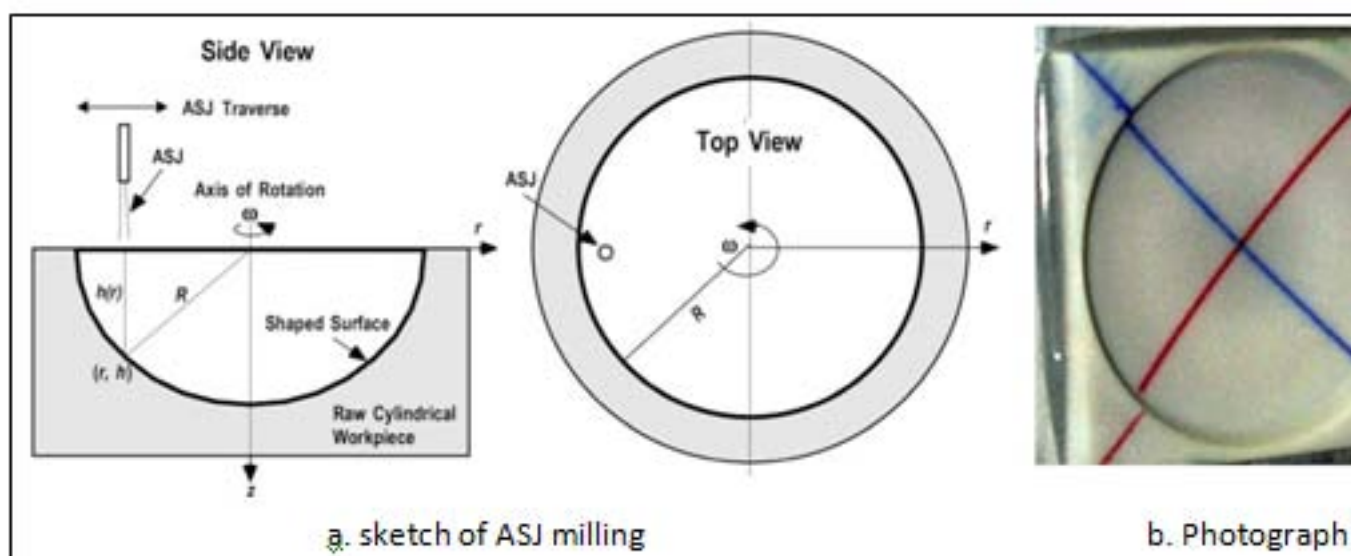
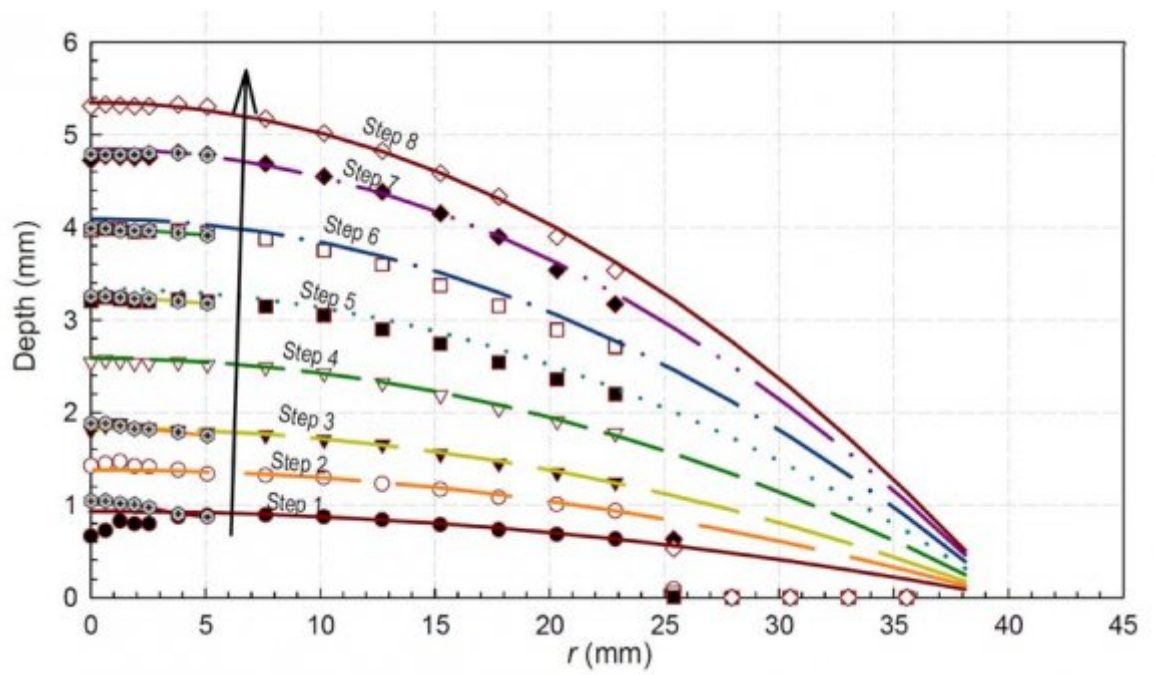
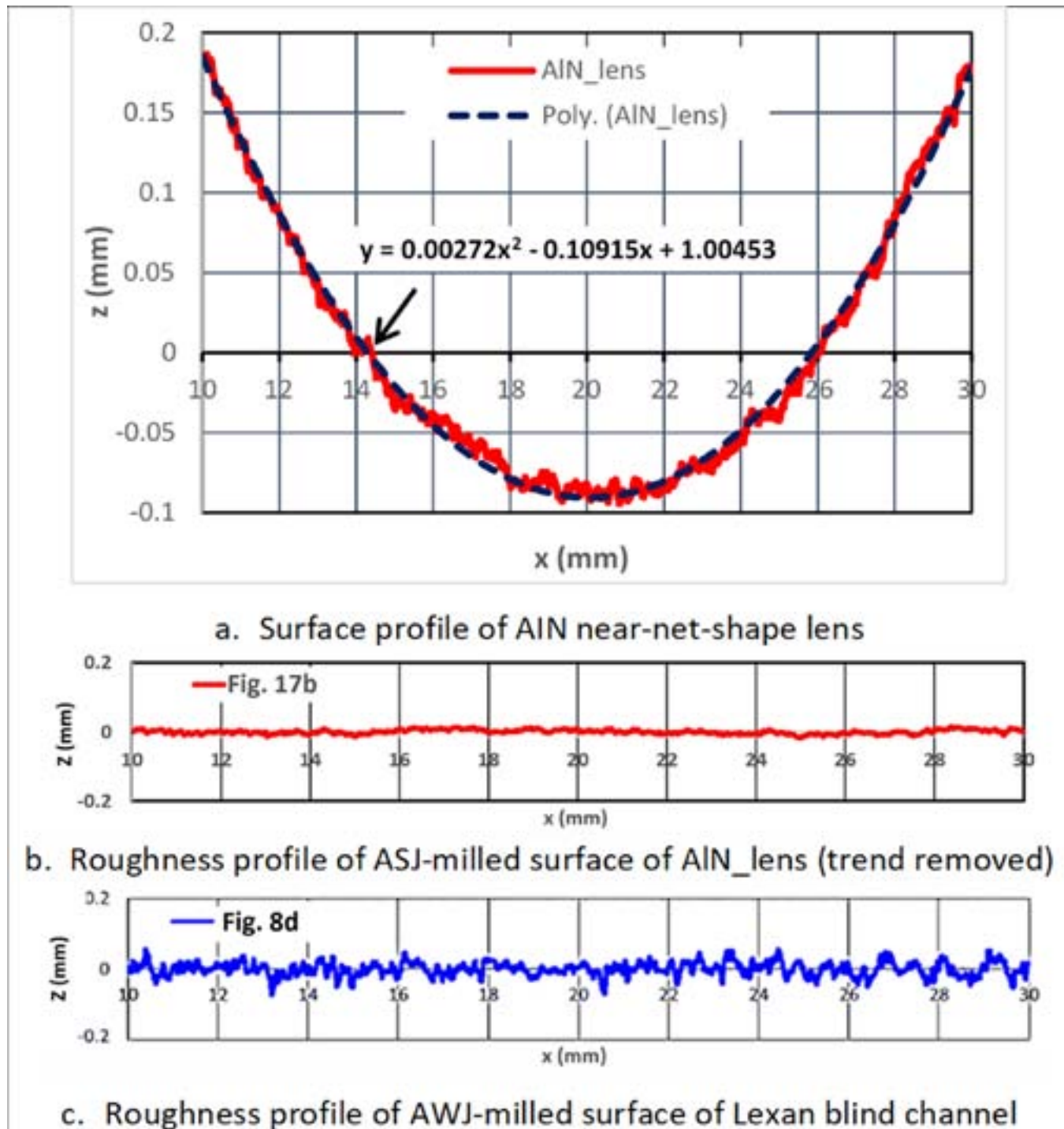


Figure 22: Figure 21 :



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Figure 23: 14 2020 Figure 22 :



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Figure 24: Figure 23 :



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Figure 25: Figure 24 :



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Figure 26: Figure 25 :Figure 26 :

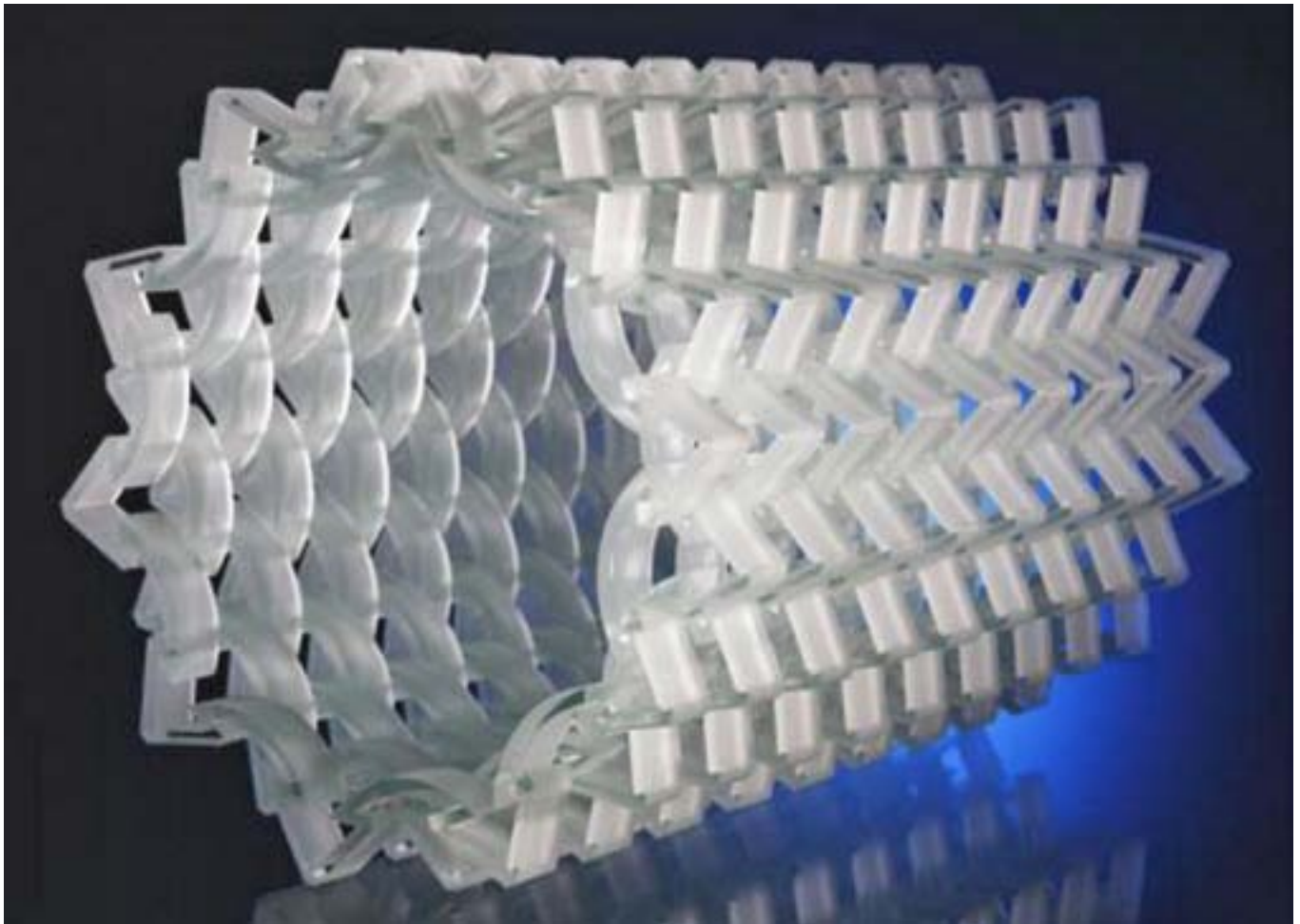


Figure 27:

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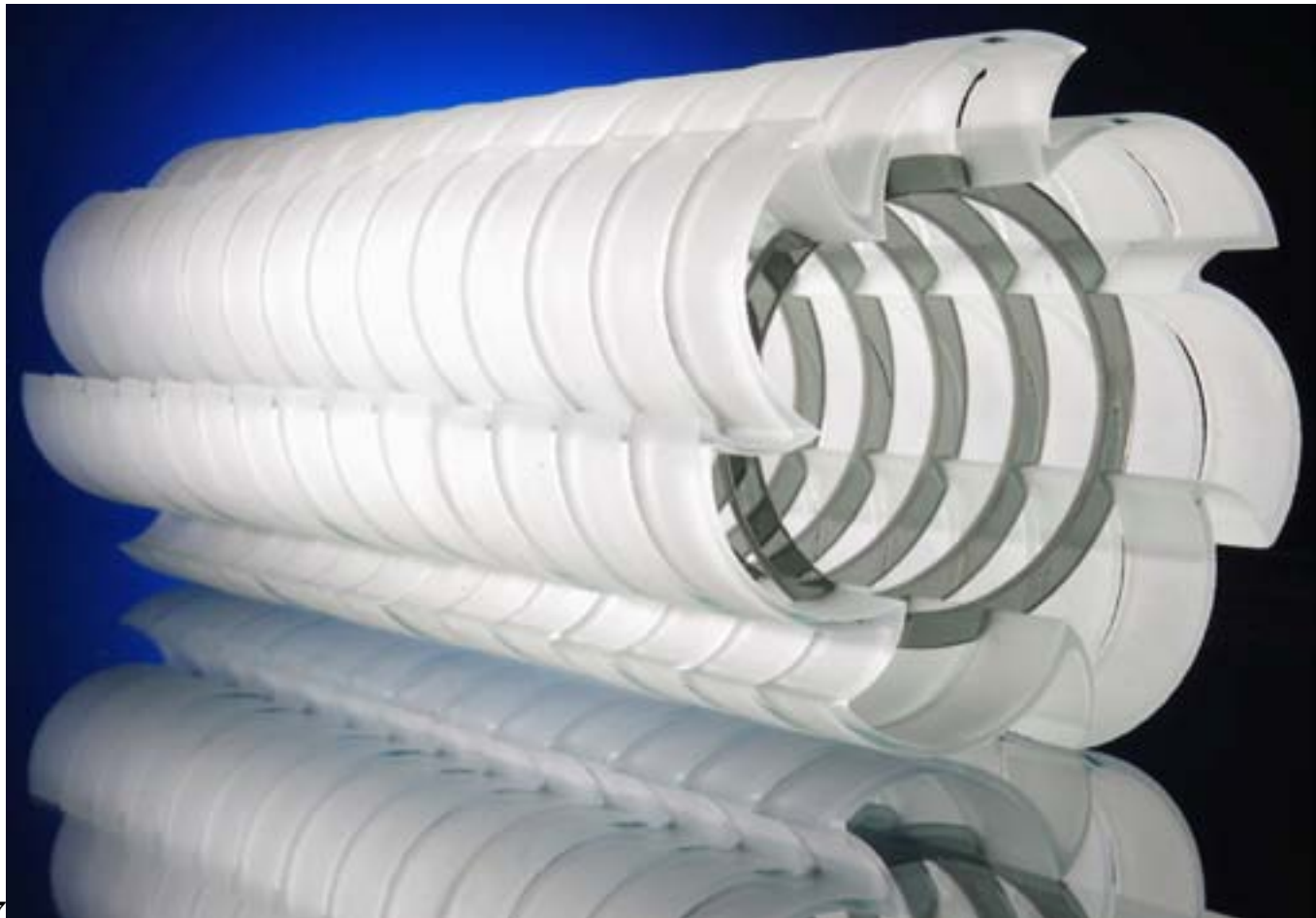


Figure 28: Figure 27 :

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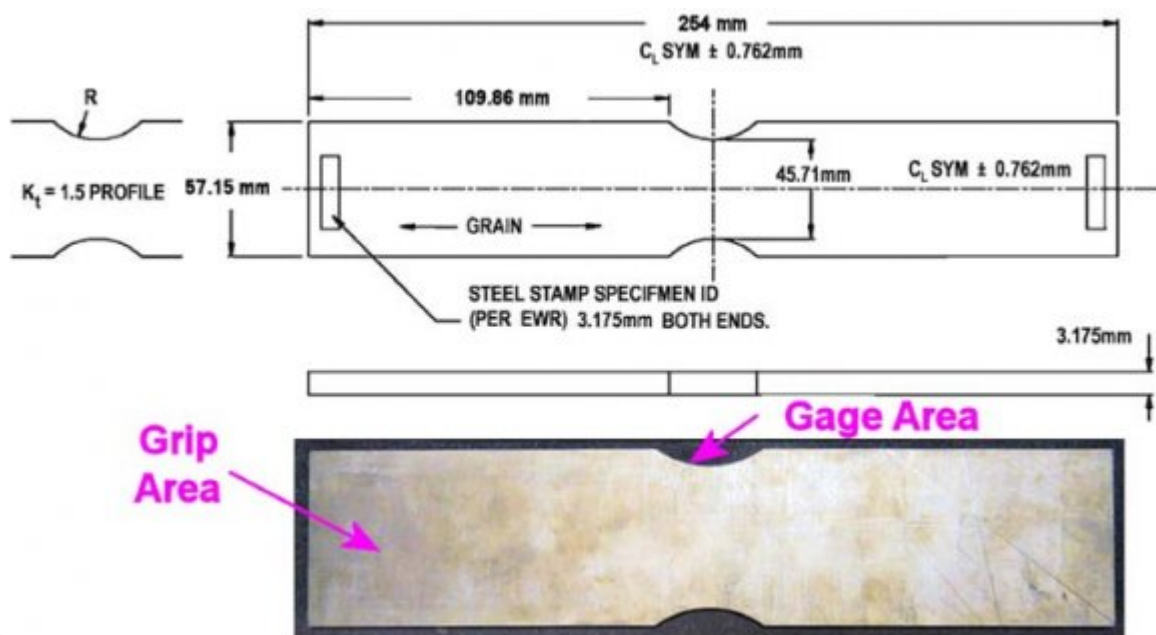


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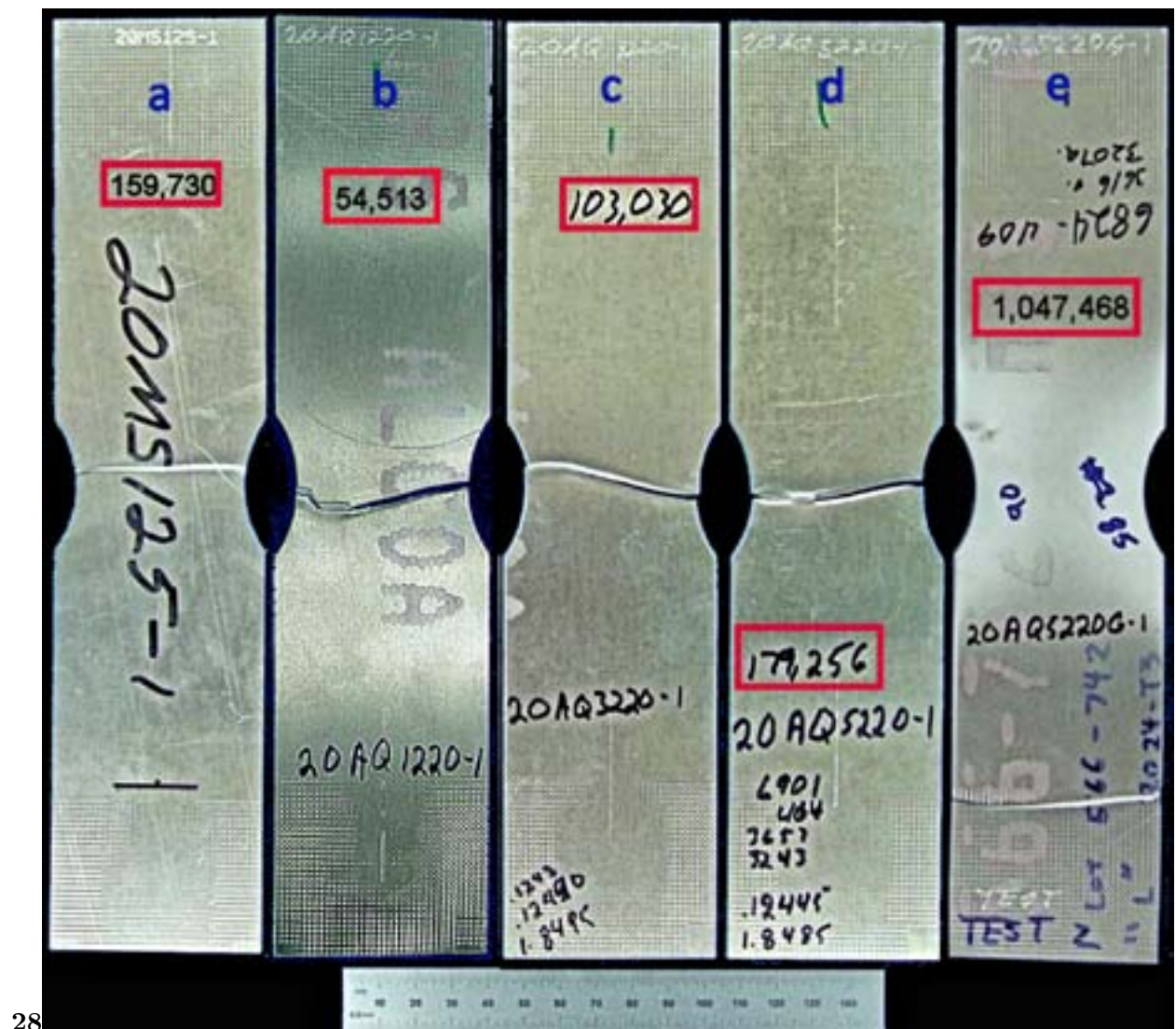


Figure 30: Figure 28 :

Acknowledgment 18 <https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-short-chain-chlorinated-paraffins> 19 [https://www.serdp-estcp.org/asetsdefense/Past-ASETS-Workshops/Past-Workshops/ASETSDefense-2018-Posters-Presentations/2018-Presentations/HumistonPresentation-meso-micro-machining-under-the-support-of-NSF-SBIR-Phase-1-and-2-Grants-\(No.-0944239-and-1058278\).](https://www.serdp-estcp.org/asetsdefense/Past-ASETS-Workshops/Past-Workshops/ASETSDefense-2018-Posters-Presentations/2018-Presentations/HumistonPresentation-meso-micro-machining-under-the-support-of-NSF-SBIR-Phase-1-and-2-Grants-(No.-0944239-and-1058278).) The author would like to thank his colleagues Dr. Axel Henning and Mr. Ernst Schubert for reviewing the paper.

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