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# HYBRID MACHINING: ABRASIVE WATERJET TECHNOLOGIES USED IN COMBINATION WITH CONVENTIONAL METAL CUTTING

Abrasive Waterjet technology is one of the fastest growing metal cutting technologies. Even so, very little published material is available on hybrid processing where abrasive waterjet cutting is one of two or more metal cutting methods. There is also limited published material on thin-walled components cut with abrasive waterjet technology. This paper makes a comparison of conventional metal cutting methods to the more unconventional abrasive waterjet technique. It will serve as a stepping stone in building knowledge aiding in hybrid machining development. It will show the possibilities and limitations during milling of thin-walled Aluminum components and then compare this to the capabilities of abrasive waterjet cutting the same components. Differences in material removal and revert control as well as in vibrations and force requirements will be reviewed. In addition, the environmental issues will be discussed and it will be determined which of the methods is more sustainable. The paper also includes a large section on process methodology.

## 1. INTRODUCTION

Although abrasive waterjet technology (AWJ) has been used for metal cutting for many years, it has only had limited applications for thin-walled components [1]. Many industrial factors drive hybrid processing forward. One such factor is cost reductions that can lead to long-term savings in both resources and environment. Revert material handling is a very large cost to manufacturers. A reduction in revert material handling by increasing the value of revert material extracted during the machining process will increase profit. More importantly, it will have a positive effect on the environment. A special application of hybrid processing is within thin-walled manufacturing where abrasive waterjet would be used in conjunction with conventional cutting technologies. Developments within this field would greatly benefit the metals industry which spends large amounts of resources on cutting tools. It will also increase their return in revert material if AWJ cutting is used as a primary cutting method. If material is cut from the interior of a solid plate, AWJ cutting will create significantly less revert material compared to for example milling.

Recent aerospace developments have led to reduced weight engine designs. Requirements for reduced emissions and fuel consumption have made aerospace

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components thinner at the same time as more difficult to machine alloys have been introduced. In addition, the competition in aerospace manufacturing has forced manufacturers to increase production rates in order to reduce cost. One of the consequences of increased material removal rates is an increased risk for vibrations during cutting operations. This, in turn, may lead to poor surface finish, reduced dimensional accuracy, excessive tool wear or complete tool failure with parts damage as a consequence, and noisier work environment. It may also lead to rework and scrap components. For thin-walled components that require the use of low machining forces, AWJ cutting is a viable option in order to avoid component distortion [2].

## 2. PROCESS METHODOLOGY

### 2.1. HYBRID MACHINING

Technological improvement of machining processes can be achieved by combining different machining actions to be used on the material being removed. A mechanical conventional single cutting action process can be combined with nonconventional machining techniques such as electro discharge machining (EDM), electrochemical machining (ECM), or laser beam machining (LBM). The reason for the development of such hybrid machining processes is mainly to make use of the combined advantages. Another reason is to avoid or reduce some adverse effects the constituent processes produce when they are individually applied.

In this work, hybrid cutting refers to a combination of cutting methods where abrasive waterjet cutting is one of two or more machining processes. Conventional machining methods, including milling, drilling, turning, and reaming are efficient, well-suited for many applications. However, there are many industrial cases where these methods become inefficient and costly. AWJ cutting is the fastest growing nonconventional cutting method and is also the most viable method to complement conventional methods. This work and the forthcoming articles in the same series will investigate specific hybrid applications to show that AWJ cutting is the natural method by choice to complement conventional cutting. It will also show examples of applications where AWJ cutting altogether may replace conventional cutting in order to save time and resources. In order to better understand the optimization of hybrid processing of AWJ and milling, these methods are here studied in parallel.

The vast majority of all AWJ applications are two-dimensional through-cutting. For such applications, AWJ is a far superior method as it can perform cutting and drilling at a large number of positions on a large sheet or plate without ever removing the work material from the machine tool table. Being a cold method, there is no thermal distortion during cutting, and subsequent heat treatment due to cutting is not required. AWJ is relatively fast, cut surfaces relatively smooth, and cutting forces virtually negligible. Vibrations, therefore, are also in effect nonexistent. In addition, it provides a high degree of maneuverability. When cutting hard or tough materials, conventional methods become very costly due to tool wear and long tool replacement cycles. The only tools that actually wear on an AWJ machine are the crystal, such as a ruby or a diamond, and the mouthpiece orifice.

Abrasive waterjet is capable of producing holes of any shape, also convergent or divergent. Extremely small diameter deep holes can be produced which often pose significant problems for conventional drilling methods. When cutting circular holes, however, the tendency of AWJ is to create tapered walls. By lowering the traverse speed, it will compensate for this tapering effect. If the traverse speed is slowed too much, however, there is a risk for the tapering to start moving outward with increasing depth. Instead of slowing the traverse speed, tilting of the nozzle may compensate for the tapering effect. Controlled correctly, this method can correct the tapering effect without affecting cutting speed [3].

Because of economic and environmental aspects, AWJ cutting has become a substitute for chemical machining, laser machining, electro discharge machining, and spray etching.

In AWJ machining, water acts as a carrier that dampens the impact effect of the abrasive on the surface. Abrasive particle grit hardness, size, type, and shape all have an effect both on MRR and on surface roughness. Material removal rate and surface roughness increase if particle hardness is increased. Harder abrasives act as rigid indentors compared to softer particles, making the hardness ratio between work piece and abrasive important [4]. By increasing abrasive hardness from 500 to 2500 Vickers, the MRR doubles. However, the increase in MRR is only slight above 1000 Vickers. Similarly, surface roughness increases significantly from 200 to 1000 Vickers and insignificantly above that. The abrasive shape also has an effect on MRR and surface roughness. More evenly shaped particles produce a lower MRR and a smoother surface. Larger abrasives and higher abrasive mass flow rates cut faster.

## 2.2. MILLING

Conventional milling of thin-walled components gives rise to chatter vibrations as the thickness of the wall reduces. This is due to increased production speeds and thereby increased MRR as component thickness and weight are reduced. Chatter vibrations in the system can be reduced by changing the offset location of the tool in relation to the workpiece. Furthermore, it is more important to have a smooth cutter exit than a smooth cutter entry in order to avoid chatter vibrations [5]. The geometric accuracy is affected by the impact of the milling forces, the location of cutter exit, and the part thickness.

## 2.3. CONTROLLED DEPTH MILLING (CDM)

During abrasive waterjet milling, material is removed to a limited depth. The fluid conditions are different from the case of through-cutting where the jet stream passes through the material. The jet is applied with several overlapping multi-ray passes across the workpiece surface. In order to obtain final geometry and form, a principle of super-positioning of several kerfs is used [6]. It is possible to produce blind pockets of controlled depths for various materials [7]. In these cases, milling time increases non-linearly with milling depth because of the loss of energy with increased distance of jet nozzle to workpiece. A goal in controlled depth milling is to minimize surface waviness. This contributes to tight tolerances and hence, additional finishing operations may be avoided [8]. It is advantageous to use high jet traverse speeds, small grit sizes, low waterjet pressures, and low jet impingement angles. However, this reduces the MRR, making the method less cost efficient. The depth of cut in the milled area is most often controlled by altering the traverse speed. A slower traverse speed increases the cutting depth. A sacrificial mask may be placed on top of the milled area in order to control surface roughness with higher precision. The stand-off distance affects the depth of cut.

### 2.4. REAMING

Reaming is a finishing operation performed with a multi-edge tool producing high-precision holes or complex geometrical shaped cutouts. When the cutout is in the interior of a component, a hole must first be bored by a different method prior to applying the reaming process. When the cutout is at the periphery of a component as in the case of a turbine blisk, reaming may be used also to initiate the cut. Reaming uses a large number of cutters and produces chips similar to milling. It is a relatively expensive and time consuming cutting method. Especially when processing hard to cut materials, it becomes a highly expensive method. Standard reaming produces circular holes and pull reaming produces virtually any geometrical shapes.

### 2.5. WATERJET GENERAL PRINCIPLES

Abrasive waterjet cutting uses very high velocity water mixed with an abrasive medium for cutting a large range of alloys. The high pressure water is let out through a nozzle equipped with a sapphire or a diamond orifice concentrating the jet onto the workpiece. The water pressure is controlled by a valve allowing for the right amount of water to pass through the nozzle. The water speeds can be in excess of 1000 m/s. The pump is the heart of a waterjet machine. There are intensifier pumps and crankshaft pumps. The difference is the way the plunger moves. In both cases, a continuously reciprocating plunger provides the pumping action. The pressure inside the pump is raised and fluid is forced out through an outlet check valve. As the direction of the plunger is reversed, low pressure fluid enters the chamber through an inlet check valve. Most waterjet systems today use high efficiency low noise crankshaft pumps.

### 2.6. MATERIAL REMOVAL PRINCIPLES

There are two principle mechanisms for material removal during AWJ cutting. Abrasion occurs when the particles collide with the surface of the workpiece. The particles are decelerated while transferring energy to the surface. Elastic and plastic deformations take place and, depending on material type, may cause cracking. Erosion implies that the material erodes because of water pressure. Water becomes incompressible at pressures above 380 MPa [9]. Above this pressure, erosion becomes more prevalent. However, the cutting depth is more dependent on abrasive particle size, mass flow rate, and incident angle, rather than the speed of the water jet. The cutting mechanisms vary depending on workpiece material. Ductile materials experiencing plastic deformation during cutting behave differently compared to brittle materials subjected to cutting through fracture. Work hardening also increases the intersection because of the strength of the material. This means that the main process is a damage mechanism, however small and limited the damage is to the workpiece. This is because it is a non-contact process causing low force and narrow kerf on the workpiece with a non-heat affected zone [10,11].

Garnet is the most common abrasive with standard mesh sizes between 80 and 200. A greater number signifies a finer garnet. By using a finer abrasive, a smother surface may be obtained but with a lower cutting speed as a result [12]. Depending on application, also olivine, aluminum oxide, glass beads, or salt particles may be used as abrasive material. When the high powered jet accelerates onto the workpiece, the abrasive particles fracture. Some grains brake up into sharp edged fragments, contributing to higher rate of abrasion. Because of a multi-point cutting tool, burr formation is reduced.

Cutting speed decreases nonlinearly with increased material thickness. This is due to the energy loss in the jet as cutting depth and jet diameter increases. Material with a thickness of 12.7 mm needs to be cut with half the traverse speed compared to the same material with a thickness of 6.35 mm. However, when the material thickness is increased to 25.4 mm, the travers speed has to be decreased to a fifth of the original value.

When cutting thicker materials, striation marks increasingly appear as cutting depth increases. As cutting speeds increase, striation marks become more prevalent. If the traverse speed is reduced to almost a standstill, the waterjet exit hole will be positioned along the axis of the entry hole and the striation marks disappear.

Numerical models have been used to predict reaction forces during AWJ cutting. Multi paths are used to produce a surface and to calculate the erosion rate when a nozzle is accelerated or decelerated. Also the waviness and surface roughness vary with both depth and length of the kerf [13].

### 2.7. KERF WIDTH

Kerf becomes narrower with increased traverse speed. This is because less abrasive particles strike the workpiece thus producing a narrower slot. Kerf also becomes narrower with higher abrasive flow rate and higher water pressure. This is because a larger number of abrasive particles share in the cutting process. Kerf taper formation may be reduced by nozzle oscillation. To avoid kerf taper, simultaneous high frequency oscillation in two perpendicular planes would be required [9]. An unstable jet affects regularity and symmetry primarily at the bottom of the kerf. Both top and bottom kerf widths increase with water pressure. The increase in jet kinetic energy opens a wider slot on the workpiece increasing kerf width. Both top and bottom kerf widths increase with standoff distance although rate of increase for the bottom kerf width is smaller. This is because of jet divergence due to lost kinetic energy as the jet collides with the workpiece. The outer rim of the diverged jet is not affected as it penetrates the lower part of the kerf. [14].

## 2.8. BURR FORMATION

Burrs form at the exit side when cutting thin sheet metal. The height of the burrs depends on traverse speed and abrasive flow rate. The material at the bottom of the cut is bent rather than removed. This is because the material is not strong enough to resist the cutting forces stemming from the jet as it exits the workpiece material. Low traverse speeds and high abrasive flow rates tend to reduce burr formation. In this case, the material has no time to deflect under the cutting forces but will be severed rather than bent. Burr height increase with standoff distance. This is due to the reduction of jet power as it flows away from the nozzle [15].

## 2.9. PRECISION CUTTING

For precision cutting, 5-axis machines may be equipped with ultrahigh pressure pumps and reduced nozzle diameters. The abrasive material may be optimized as nanometer sized particles of aluminum oxide [16]. There has also been modelling work done in precision machining with miniaturized nozzles [17]. The models take advantage of submerging the work piece in the surrounding fluid while micromachining shallow channels in the material. This made it possible to use abrasive waterjets to perform controlled depth micromilling. The model showed accurately that cut channels become progressively wider while channels become deeper.

Micromachining has developed for milling with jet diameters from 30 to 70 μm carrying nanometer sized particles of aluminum oxide. Claims are that cutting should be possible with jet diameters less than 10 μm [18]. Clogging of the nozzle is a limitation. When the abrasive medium decreases in size it has the tendency of sticking. Also Venturi-generated vacuum can have a clogging effect.

Precision drilling of small diameter holes in advanced aircraft engine components have been made using AWJ technology. The results indicate that accuracy and repeatability can be ensured in air flow and hole size requirements. By varying the pressure while drilling in composite materials, hole size can be controlled. This requires continuous adaptation. Sensor systems need further development to fully control this technique [19].

## 2.10. SURFACE ROUGHNESS

The surface quality is better at the upper half of the cut and worse from the middle of the thickness downward. Surface roughness becomes reduced with increased abrasive flow rate because of a higher number of impacts and cutting edges per unit area. Surface roughness is also reduced for increased water pressure because some of the brittle abrasive particles break down into smaller unevenly sharp particles in the highly pressurized jet. At the same time, cutting becomes more efficient due to the increase in kinetic energy. Traverse speed and standoff distance also affect surface quality [20]. As the traverse speed increases, fewer abrasive particles per unit area pass the cutting area, resulting in a rougher surface. The jet diameter expands hydro-dynamically when standoff distance is increased resulting in an increased surface roughness. Therefore, the surface finish is better at the top of a cut near the nozzle. Surface roughness increases at low impingement angles due to the suppression of secondary milling. Surface roughness can be minimized by combining small-sized abrasive grits with lower jet impingement angles.

### 2.11. SURFACE WAVINESS

Surface waviness is affected by water pressure, abrasive flow rate, and traverse speed as these changes dynamically during the process [14]. The steadiness of motion is therefore important, especially for softer, easy to cut materials. For hard materials, small variations in the dynamic parameters will not affect the jet-produced waviness to any significant degree. Waviness increases as the depth of cut increases. High traverse speeds reduce surface waviness. When secondary milling is conducted at high traverse speeds, grit embedment increases with increasing impact angle. This is because of a higher impulse during impact as the impingement angle is raised.

## 3. EXPERIMENTAL SETUP, RESULTS, AND DISCUSSION

Aluminum 6082 plate was used for the experiment. A component was cut from the interior of the plate with geometry of four thin-walled structures. The walls had thicknesses of 1.0 mm, 0.8 mm, 0.6 mm, and 0.4 mm respectively. For milling operations, both upmilling and downmilling were used to study the effects of vibrations during processing. A five-axis milling machine equipped with a 10 mm two-tooth end mill was used. The spindle speed was set at 5000 RPM, feed rate at 900 m/min., and depth of cut at 3 mm. The waterjet cutting machine was a small table precision machine equipped with a 30 degree tilting head, 0.5 mm orifice, and a garnet grit size of 120 (see Fig. 1).

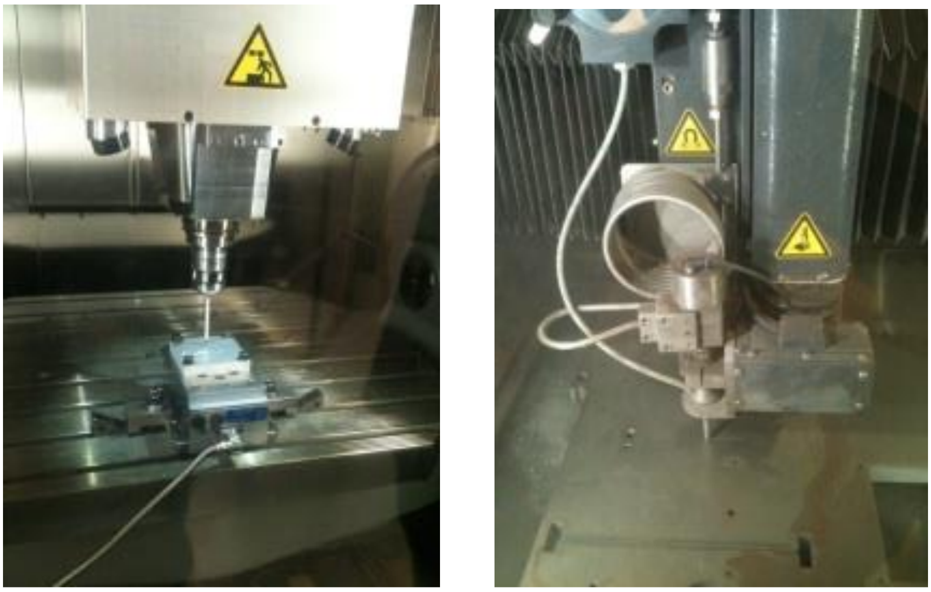

Fig. 1. Milling setup (left) and waterjet head (right) used during experiment

The component was cut from the interior of a solid plate and revert material produced was measured. It was found to be 10 grams for the AWJ compared with 200 grams for the mill, i.e. 20 times greater for milling than for AWJ cutting. The large difference stems from the fact that the mill used had a diameter of 10 mm. The volume removed was therefore much greater for the mill than for the 0.5 mm orifice AWJ cutting jet. The mill also exhibited rounded corners where the tool turned around. When straight corners are required, some post processing will be needed if milling is used. The AWJ is in this regard superior as it can turn around creating relatively square corners. Therefore, material lost during the process was significantly less and precision in the corners much greater for the AWJ cutter. In addition, the standard end mill was unable to start at an interior point of the plate.

The abrasive waterjet has the advantage that it can penetrate the work piece at any point. Cutting or cooling fluids are often used during milling but are not necessary during AWJ cutting. The environmental effects from these fluids plus the excess waste of material during milling make AWJ cutting a much more sustainable method than milling.

The downmilling method was able to cut the four walls without any visible deformations. When the same component was cut using the upmilling method, not even the largest thickness wall of 1.0mm could be cut. The chatter vibrations proved too large and the wall failed and severed (see Fig. 2). The differences in vibrations and force requirements for these two methods are depicted in Fig. 3.

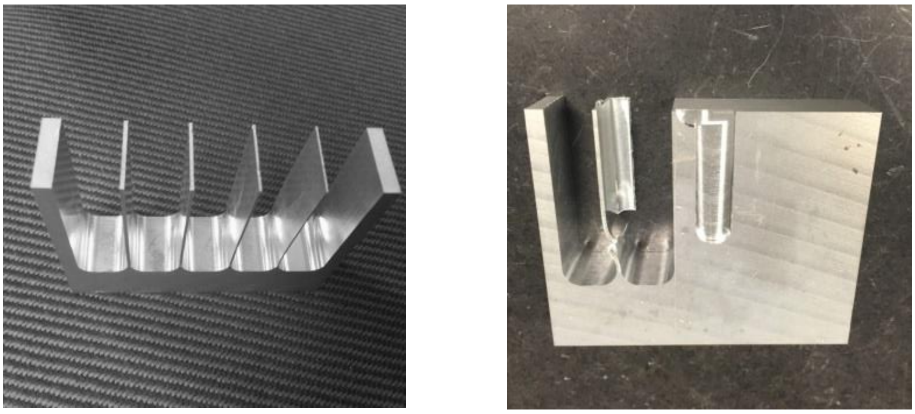

Fig. 2. Downmilling (left) and upmilling (right) attempting to cut thin walls

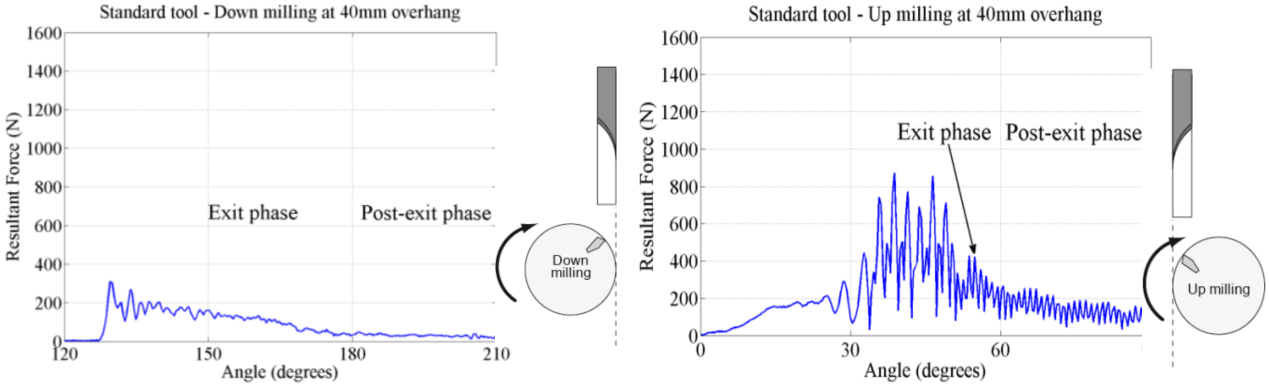

Fig. 3. Vibrations and force requirements for downmilling (left) and upmilling (right)

The vibration patterns shown in Fig. 3 were proven correct by machining the component used in this study. Using downmilling, all four walls in the component could be cut without any visibly noticeable deformations. However, when using upmilling, even the thickest wall (1.0 mm) failed and severed. The higher force requirements and the large amounts of self-induced vibrations for upmilling are due to the high values of the specific cutting force $k_c$ when the tool enters the workpiece and the material is being plastically deformed prior to commencing cutting. They are also due to the fact that the cutter exits the workpiece in the most flexible direction.

The amount and shape of revert material that can be recycled into new material production is also of interest. Milling produces chips of large volumes compared to its weight. Recycling plants usually pay significantly less for revert chips than for revert solids. Revert produced during AWJ cutting is much more favorable. It is obtained in solid chunks of material providing a higher value for revert material.

The vibrations during downmilling are significantly greater than for abrasive waterjet cutting. AWJ cutting only produces some minor initial forces onto the workpiece but after the jet penetrates the material, cutting forces affecting the component can be neglected. Therefore, vibrations affecting the structure can also be neglected. However, forces stemming from material tension will always be inherent in a thin wall as it is separated from the main material plate.

Precision of the cut is dependent on vibrations and forces affecting the cutting zone. Therefore, milling shows larger deviations from a perfectly flat surface than AWJ cutting. The result from cutting the component using AWJ is shown in Fig. 4. A slow traverse speed was used to achieve a high quality surface. The cutting was done with the workpiece suspended in-air.

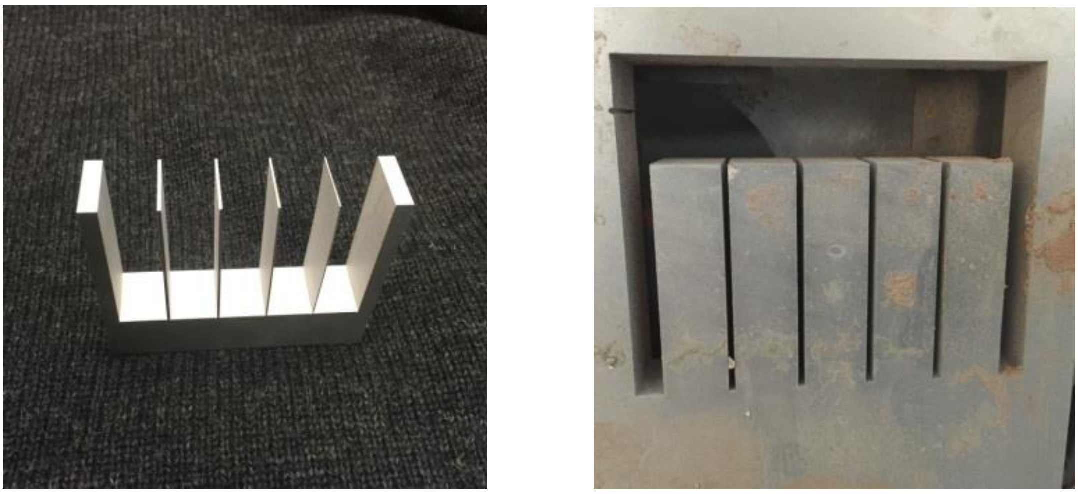

Fig. 4. Abrasive waterjet cut component (left) and revert potential (right)

The following experiment was performed using a production waterjet machine (see Fig. 5). A simple profile was cut out from the interior of 20 mm Aluminum 6082 plate. Outside the profile, a thin wall of 0.4 mm thickness was cut that subsequently could be placed onto the outside of the original cut part (see Fig. 6). This type of thin-walled component cannot be produced using a milling machine. A standard production waterjet machine will cut it without difficulty. The waterjet cutting machine was a 2x4 m large table production machine equipped with a 15 degree tilting head, 8mm orifice, and a garnet grit size of 80. A slow traverse speed was used to achieve a high quality surface. The cutting was done with the workpiece immerged in water.

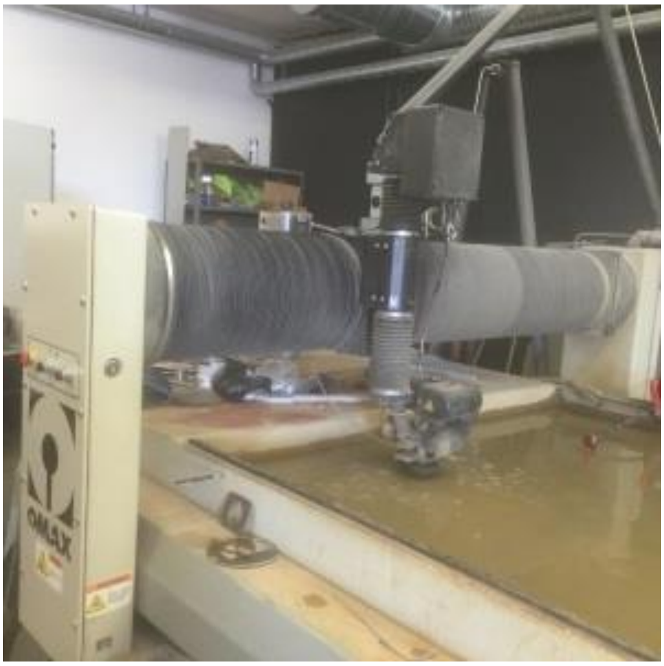

Fig. 5. Production waterjet machine

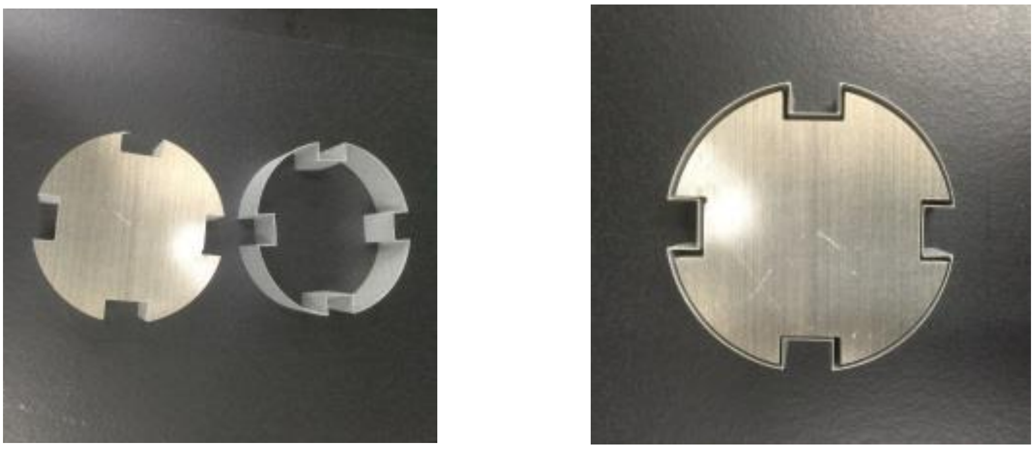

Fig. 6. Profile cut by abrasive waterjet with wall next to it (left) and fitted onto it (right)

This type of thin-walled component cannot be cut by conventional metal cutting machines, especially not by milling. If the wall thickness were increased significantly making it possible to mill both the original profile and the wall, the amount of material lost would be inhibitive. The square corners of the cutouts would also be very difficult, if not impossible, to mill. Another inherent issue while attempting the milling of the thin-walled portion of the component is chatter. Any level of self-induced resonance would make the wall fracture.

## 4. CONCLUSIONS

Hybrid processing is a most viable option in order for the metals industry to stay competitive and sustainable. Vibrations and cutting forces cause precision issues during machining. Abrasive waterjet cutting does not cause any significant vibrations on the component since the cutting forces in effect can be neglected. Milling, on the other hand, can cause noticeable self-induced vibrations due to very large cutting forces. In the experiments, upmilling was shown to fail even at the largest wall thickness whereas downmilling managed to cut all four walls.

The amount of material lost during the process is approximately 20 times larger for milling than for abrasive waterjet cutting. The chips produced during milling also create a much larger material volume to weight ratio. This increases revert storage volumes and reduces revert value for the parts producer. Abrasive waterjet cutting on the other hand leaves chunks of revert material.

The absence of cutting fluids and the negligible amount of material loss makes abrasive waterjet cutting a much more sustainable metal cutting method compared to milling. The negative effects on the environment are also minute for abrasive waterjet cutting.

Milling cannot cut square corners, at least not the 10mm end mill used during this experiment. This means that some post processing would be required if milling were chosen as cutting method. Abrasive waterjet, on the other hand, cuts square corners with high precision, further contributing to an advantageous material revert situation. The abrasive waterjet can start cutting at any interior point of the material whereas a standard end mill needs to start cutting at an edge. By combining abrasive waterjet with milling in a hybrid machining environment, the process can be optimized for geometry, precision, and sustainability.

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