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ACCURATE HOLE DRILLING USING AN ABRASIVE WATER JET IN TITANIUM

S. Zhang, P. Nambiath, G. Galecki, D.A. Summers
University of Missouri-Rolla
Rolla, Missouri, U.S.A.

D. Bowden
The Boeing Company
St. Louis, Missouri, U.S.A.

ABSTRACT

Abrasive slurry jets (ASJ) and abrasive waterjets (AWJ) offer a low temperature, low damage method for machining titanium. However to achieve the required precision both in cutting and milling of materials, abrasive waterjet systems must operate within well defined performance parameters.

In order to define these parameters a series of experiments are described using the titanium alloy Ti6Al4V. Two different applications formed the initial focus for the investigation. The first is the ability to precisely cut holes, and the second relates to the precision milling of pockets in the target surface. For both operations, the accuracy of verticality of the walls cut forms an important control on acceptable performance. Tests to determine the effect of cutting speed on wall quality have shown an interesting result. As cutting speed increases wall quality decreases, to a certain point, and then with further increase in speed begins to increase again. Optimizing performance therefore can potentially not only meet the verticality criterion, but also achieve other required goals of cutting performance. The relationships between surface quality, geometrical features and machining parameters thus become an integrated suite of interactions, that continue to be defined as a function of target material and geometry. Surface roughness and micro-structural surface features are a critical aspect of acceptable quality. The operational requirements to achieve defined standards of surface roughness and hole tolerance are discussed, with illustrations as to how they may be achieved.

1. INTRODUCTION

The ability of abrasive waterjets to carry out accurate cutting of titanium and other exotic metals has been known for some time. In the conventional shaping of parts, and in the creation of holes and other cavities, abrasive waterjets have usually been able to achieve cutting precision of around 0.01 inches (0.25 mm) without the need for additional compensation to the cut. This is achieved in a way that can leave the surface of adequate quality for some final applications.

In the aerospace industry, however, cutting precision is required to a higher tolerance, with not only the accuracy in placement and dimension defined, but also the quality of the surfaces that are left after cutting. In the past this has, on occasion, led to the need to carry out final reaming cuts following the initial placement of holes, in order to ensure the correct tolerances.

The Rock Mechanics and Explosives Research Center (RMERC) at the University of Missouri-Rolla (UMR) is currently working as a part of the UMR Center for Aerospace Manufacturing Technology (CAMT) to develop the tools and processes that will assist companies such as Boeing (the current Prime Center Partner) to construct the airframes of tomorrow. This program is funded by the U.S. Air Force, and the support is gratefully acknowledged.

As a part of this program the RMERC and Boeing are teamed to examine ways of increasing the cutting precision of abrasive waterjets and slurries, and to look into processes by which controlled depth cutting can be achieved in different materials, but with the initial focus on shaping titanium. In order to improve capabilities it is important to begin with a definition of the current system capabilities.

A preliminary set of experiments was therefore set up to define the basic parameters that control both surface roughness and hole precision. This initial work was carried out using an X-Y table and software from OMAX, and using a KMT nozzle design, with a 0.010:0.030 inch (0.25:0.75 mm) diameter for jet and focusing tube. A model XXX Ingersoll Rand pump was used to supply water under pressure to the nozzle, and in this initial work all the tests were carried out at a pressure of 40,000 psi (280 MPa) with an initial abrasive feed rate (AFR) of 0.62 lb (0.28 kg) per minute of 80 mesh Barton garnet. (Please note that company names are used for the sake of identification only and do not provide any endorsement of these products by the University, Boeing or the U.S. Air Force).

2. INITIAL TAPER EVALUATION

When a high pressure waterjet moves across a target surface, it will cut a slot that does not, conventionally, have straight sizes. Rather if a circular cut is being made, then the hole walls will taper in with depth. This taper is controlled by a number of different variables, and one of the ways in which the angle can be reduced is through a change in the cutting speed. Such a taper is, however, only marginally acceptable for aircraft construction. The defined dimensions that the hole must achieve have relatively tight tolerances (Fig. 1 and Table 1).

As the traverse speed is reduced, the effective cutting structure of the jet changes and so the initial inward taper of the sides of the cut reduce as speed drops. Thus one of the features that is used in cutting table programs is a requested input on the surface quality required, since lower quality cuts can be cut more rapidly. To determine initially what this change in programmed cut quality would have on wall angle, a series of cuts were made (Fig. 2) in 0.5-inch (12.7 mm) thick titanium. The cuts were made at 4 diameters, and at each of the five settings for wall quality that came with the machine. The upper and lower diameters of the holes generated were then measured and an average change in dimension calculated for each (Table 2).

It is interesting to note that as the machine had slowed the cutting head to improve surface quality, so the taper of the wall had gone from unacceptable because of too great a taper inward to the point where, at the slowest cutting speed, and highest surface quality setting, the taper had exceeded acceptable bounds because it was inclining outward too much. The information suggested that before going much further with the speed correlation alone, it might be useful to determine what the actual quality of the surfaces generated at the different speeds were.

Accordingly a second test series was carried out. In this, linear cuts were made through samples of titanium and the surface roughness of the cut was measured at the top and bottom. The maximum roughness (R_A) acceptable was a value of 125. Sample surfaces are shown (Figs. 3, 4 and 5) and it was noted that both the top and bottom measurements showed a steady increase in roughness as the speed of the cut incremented. The final surface where the quality was acceptable, at the top, though not at the bottom, was at a traverse speed of 3.0 in/min (76 mm/min). This provides a benchmark to the program, since changes in other parameters will allow an improvement in cutting.

It is interesting to note that at this cutting speed the time taken to drill holes through the plate were equivalent to those achievable with a mechanical drill but significantly faster than the recommended cutting time in the existing program.

With a cutting speed that has now been defined, it seemed appropriate to revisit the effect of cutting speed on hole taper. Accordingly a third series of holes and linear cuts were now made to determine hole taper angle as a function of traverse speed. The intent was to determine initially, the change in wall angle, and this was determined through a simple comparative measurement on the samples.

From the results (Fig. 6) it can be seen that the velocity at which zero hole taper occurs lies at 0.3 inch/min (7.5 mm/min). To cut parts at this velocity would take about ten times as long as conventional cutting, and thus an alternate solution is required.

3. DEVELOPMENT OF A FIVE-AXIS SYSTEM

The tools used up to this point have been oriented toward a two-axis cutting system. However if the nozzle is inclined by a small increment of arc then potentially the jet orientation could compensate for the angle of the cut. At 3.0 inch/min for example, the taper on the wall through a half-inch titanium plate was around 1^{o}. Thus if the head were tilted at this angle the jet should, theoretically, cut a vertical wall. In order to accomplish this additional geometric capability a PAR Vector 5-axis cutting system has been used, and the work from this point forward has been carried out using that machine, and a larger 100-hp KMT pump.

We recognize that tilting the head is not a novel conclusion and other speakers will address a similar theme at this conference (Ref. 1). In order to move the program forward, since our goals lie beyond this initial objective, a matrix was now generated to develop data on the effect of a small angle of tilt on the cutting head, as the jet cuts holes of different diameter in titanium plates of differing thickness.

In order to quickly obtain a significant amount of data a sample test piece was designed, in which four sets of 6 differing diameter holes were cut in a set pattern in each plate. The sample was then separated from the main body of metal by a relieving cut all around the sample section. The difference between the four sets of holes cut in each plate was the angle at which the jet intersected the plate. An initial design (Fig. 7) was cut with the intervening walls between holes as small as 0.02 in. (0.5 mm). Because of the way in which the holes were cut, this pattern allowed a demonstration of the gentleness of the waterjet cut, since the final hole in the pattern was cut into the metal held by these thin strips, without distortion (Fig. 8).

However, in cutting the pieces at this level of accuracy, one potentially confounding factor had not been considered. Many of the manufacturing processes that create metal shapes can leave a residual stress within the material. As the cut relieves these stresses, and removes some of the metal that has the strength to resist that stress, the part can distort. At these levels of accuracy even a small strain can move the wall out of compliance. And where the wall thickness to the hole is as small as was being cut, then this is small enough to be distorted by the remaining residual stress both during, and after the immediately local cutting.

Accordingly the sample shape was modified to give a minimum wall thickness of 0.125 in. (3.175 mm) (Fig. 9).

In cutting these samples some limits on machine performance became evident (at small diameters the head cannot rotate at the speed needed to maintain the 3-inch traverse speed) but otherwise the matrix was completed as a full factorial, examining the effects of abrasive feed rate, pressure and nozzle geometry on the quality and angle of the hole surfaces, cutting the holes with an inclination of 0^{0}, 0.5^{0}, 0.75^{0} and 1.0^{0}. The complete factorial results have yet to be compiled.

4. CONTROLLED DEPTH CUTTING AND MILLING

The precision cutting of parts requires not only contour shaping, and hole drilling, but often also the partial removal of internal volumes, usually by milling. Historically, where waterjets have been used for this purpose a masking technique (Ref. 2) has been used to cover the areas that are to be left, while the open areas are eaten away by successive passes of the abrasive nozzle over the part:mask combination.

Two aspects of milling are being currently evaluated. The first is the use of an abrasive slurry replacement for the conventional abrasive waterjet tool. In making the change to the ASJ system, again it is important to have initial background data on the current performance of the existing system in order to make value judgments on the benefits of the change. The second consideration, is to examine the potential for removing the unwanted material in sizes other than the fine powder generated by full volume milling.

For example, when cutting a chamfered hole in the titanium, it is possible to remove most of the unwanted metal as a single fragment (Fig. 10). It seems logical that in the larger volume removals of bulk milling that it might be possible to achieve a similar improvement in efficiency if significant volumes of the material are cut out in blocks rather than fine milled. To do that however may, at this stage in the development of the waterjet:computer control interface, require that the jet cut to an accurately specified depth.

Thus as an additional part of this work, the program is looking at the constraints on accurately controlled depth cutting (Fig. 12) both in linear cutting and full volume material removal (Fig. 13). Some of the initial parameters that control milling with an oscillating head have previously been discussed (Ref. 3) in an earlier paper. There is, simplistically, some optimization that must be required in the operation of a milling head that only removes the desired volume, to ensure that it only cuts to the depth required. This becomes of particular concern in areas where the head must change direction in moving around the space (the corners shown in Fig. 13). At present there is an ongoing evaluation dynamically change operational parameters during the milling process to more accurately control depths milled and to create a more accurately aligned floor. It should be noted that the controls on the angle of cutting, which are being derived in the other part of the program described earlier, will also be integrated into this part of the effort.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Ref. 1. Zeng, J., Olsen, J, Olsen, C and Guglielmetti, B. “Taper-free Abrasive Waterjet Cutting with a Tilting Head”, Proc. 2005 American Waterjet Conference, Houston 2005 (in press).

Ref. 2. Hashish, M. “Trends Towards New Applications of Waterjet Technology”, in Abrasive Water Jet – a View on the Future, edited by M. Monno and M. Strano, ITIA Series.

Ref. 3. Zhang, S., Summers, D.A. and Shepherd, J.D., “Experimental Investigation of Rectangular Pocket Milling with Abrasive Water Jet Using Specially Designed Tool,” Proc. 17th Int. Conference on Water Jetting, Mainz, Germany, Sept. 2004, pp. 435 – 448.

Table 1. Tolerance requirements for holes to be drilled in titanium structures.

Nominal Diameter	Hole Diameter (in.)	Shank Diameter (in.)	Fit
3/16	0.190 + 0.004 – 0.000	0.1890 – 0.1895	0.0005 – 0.0050
1/4	0.250 + 0.004 – 0.000	0.2490 – 0.2495	0.0005 – 0.0050
5/16	0.3125 + 0.004 – 0.000	0.3115 – 0.3120	0.0005 – 0.0050
3/8	0.375 + 0.004 – 0.000	0.3740 – 0.3745	0.0005 – 0.0050
7/16	0.4375 + 0.004 – 0.000	0.4365 – 0.4370	0.0005 – 0.0050

Table 2. Measured hole diameter changes as a function of hole diameter and surface quality.

Quality	Hole 1 0.18 in.	Hole 2 0.24 in.	Hole 3 0.36 in.	Hole 4 0.42 in.	Average	Average O.K.?
Omax 1	- 0.004	- 0.004	- 0.0015	- 0.0120	- 0.0055	No
Omax 2	0.003	0.0045	0.001	0.004	0.00325	Yes
Omax 3	0.002	0.0005	0.002	0.005	0.0029	Yes
Omax 4	0.0015	0.001	0.0045	0.004	0.00275	Yes
Omax 5	0.003	0.004	0.005	0.006	0.0045	No

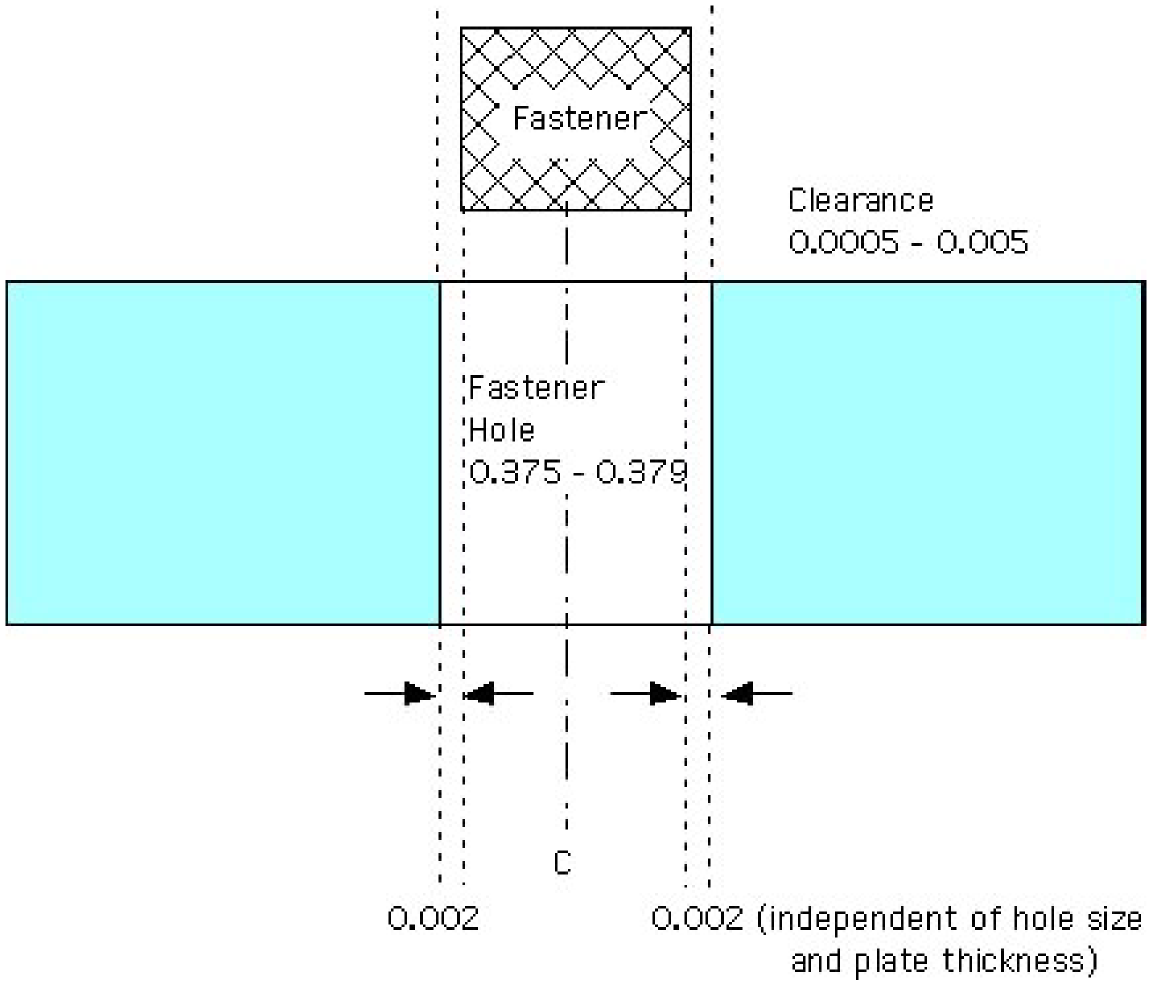

Figure 1. Example of the required dimensional tolerance on a 3/8 fastener.

Figure 2. Initial holes cut in titanium at different cut qualities.

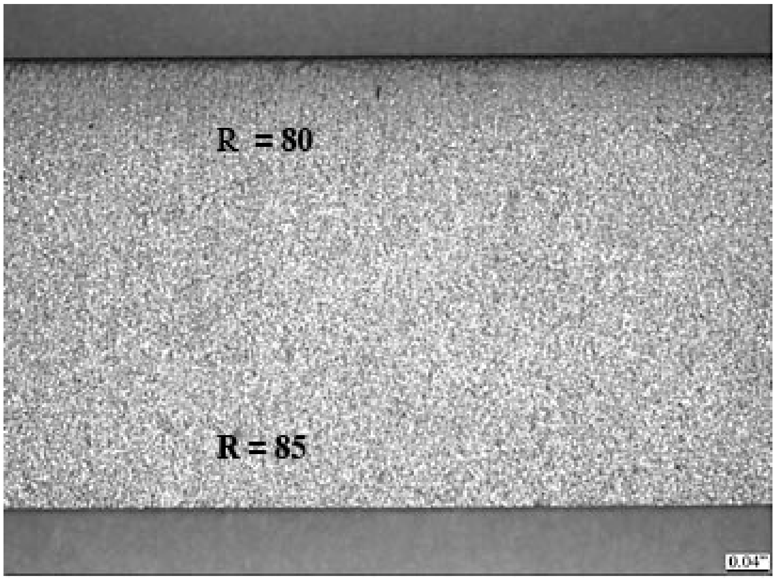

Figure 3. Surface roughness measurements at 0.25 inch/min, R_A values measured near the top and bottom of the sample, cut from the right.

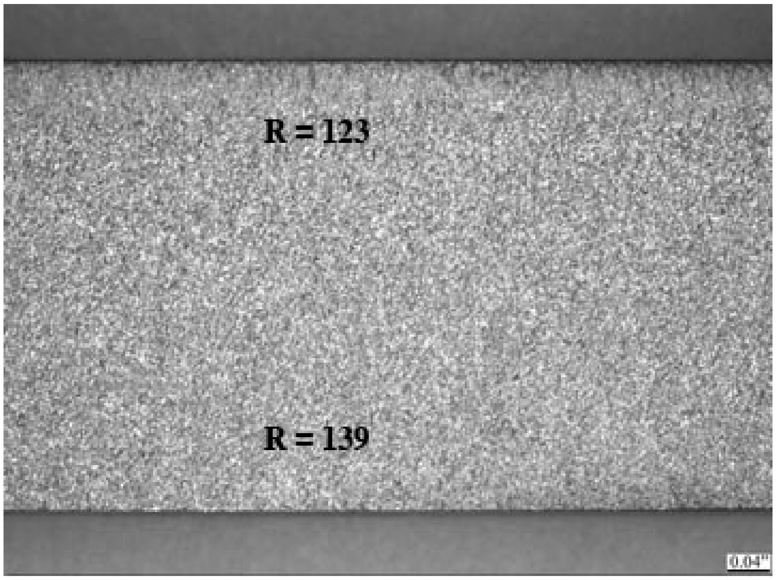

Figure 4. Surface roughness measurements at 3.0 inch/min, R_A values measured near the top and bottom of the sample, cut from the right.

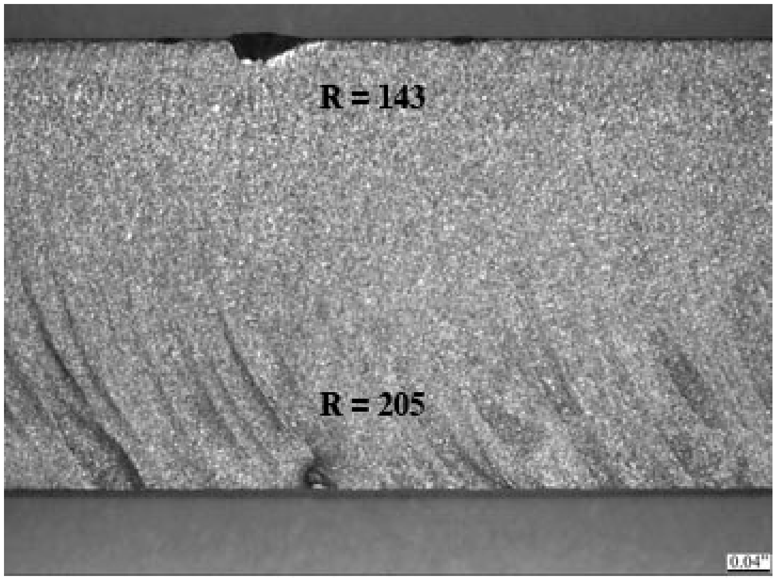

Figure 5. Surface roughness measurements at 7.0 inch/min, R_A values measured near the top and bottom of the sample, cut from the right.

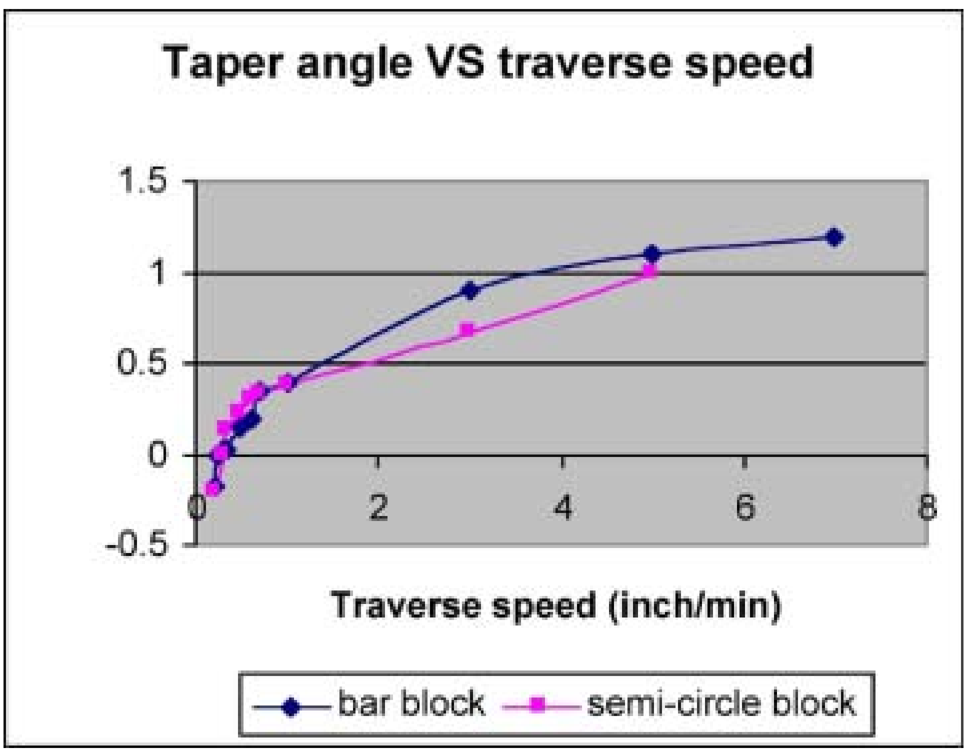

Figure 6. The effect of traverse speed on cut taper in titanium.

Figure 7. Initial pattern of test holes, the numbers shows the order in which each series of four holes at the same size, but differing nozzle angle, are cut.

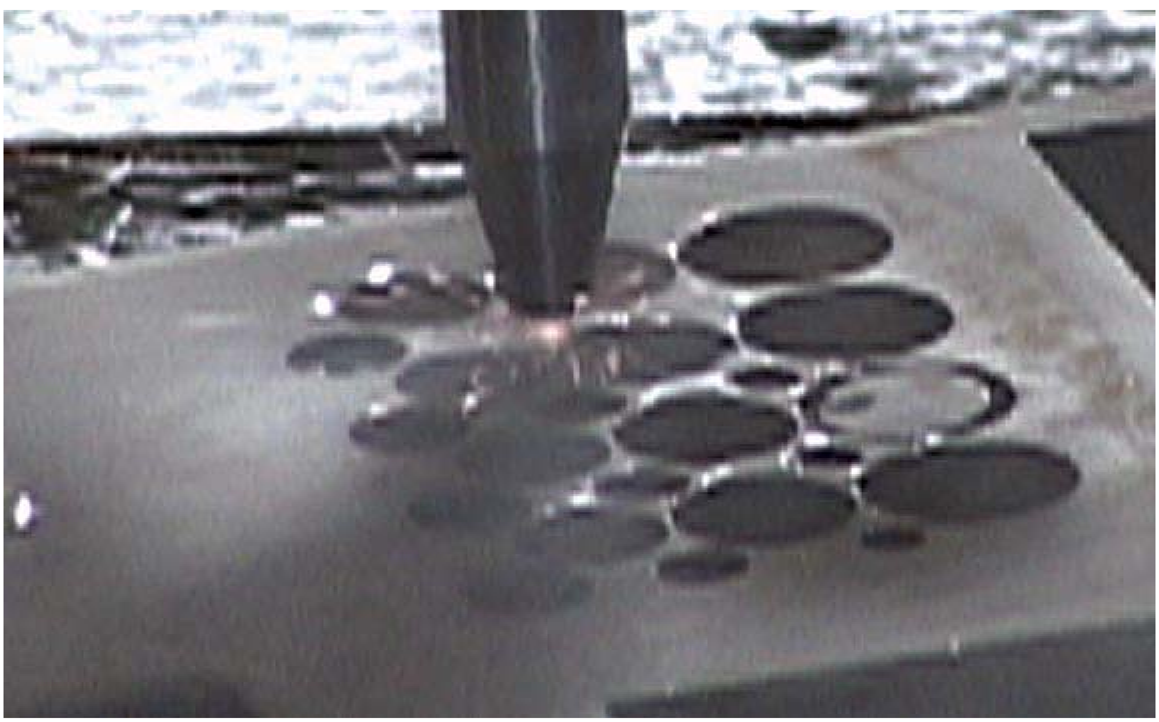

Figure 8. The cutting of one of the interior holes in a piece held by thin bridges (from video).

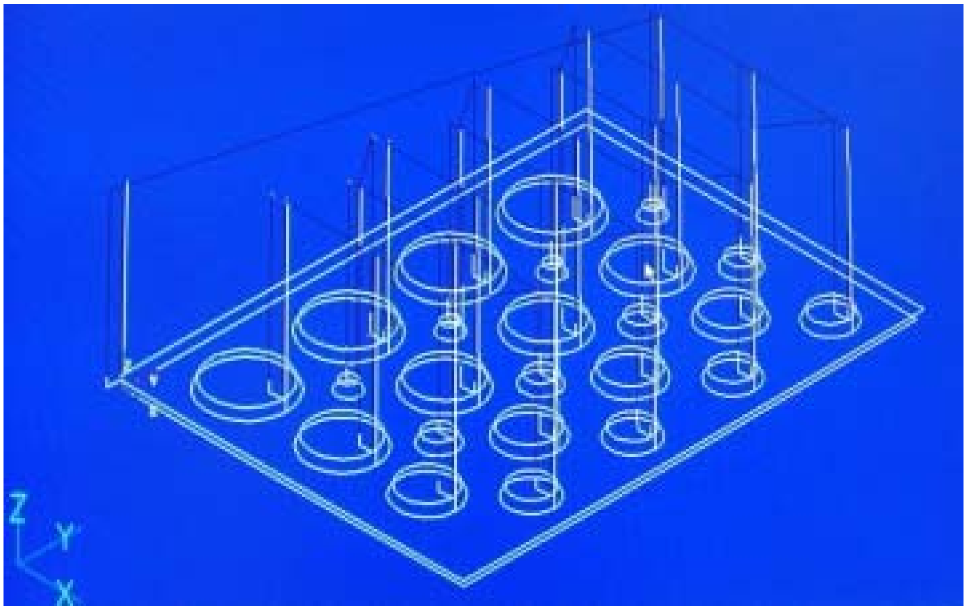

Figure 9. New part layout.

Figure 10. AWJ cut chamfered hole scrap contrasted with conventional machining scrap.

Figure 11. Precision depth cutting to isolate blocks of material.

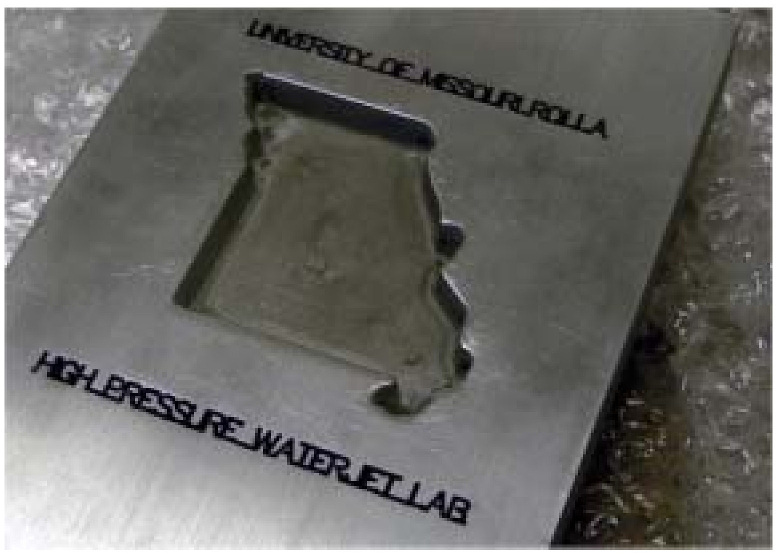

Figure 12. Contour milling showing the excess depth cut at the turning points.