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ABRASIVE WATERJET CUTTING USING A ROTATING AXIS MOTION CONTROL

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ABSTRACT

This paper deals with abrasive waterjet and the use of a 4-axis motion control in which one axis is a rotating axis controlling the motion of the work-piece. Manufacturing of solid parts from bulk pieces of material fixtured in a chuck or similar is presented and discussed. The manipulation include indexing the part using the rotating b-axis, cutting the part from different angles, as well as controlling several or all axes simultaneously. Also is presented the possibility of producing single-curved surfaces by continuously rotating the b-axis, while moving the jet in the axial direction of the work-piece.

The advantages of manipulating the work-piece in the manner described, instead of the nozzle, are discussed outgoing from practical experiences. A difficulty in this type of machining is the accessibility of the jet which can require a larger stand-off distance than normally used. This aspect is investigated experimentally in the paper.

It was found that complex parts can be manufactured with a machine concept that still is relatively simple. However, CAD/CAM software for 3D parts is essential when dealing with the more complex types of parts made. For this reason a CAM postprocessor was also developed for the presented machine configuration, and then used in practical cases.

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1. INTRODUCTION

Abrasive waterjet (AWJ) has due to its versatility become widely accepted as a tool for manufacturing parts out of virtually any material for various applications. The method is used in small job shops as well as in advanced manufacturing facilities. The most common application however of AWJ is sheet metal cutting, mainly in relatively thick dimensions. Typically the cutting tables are 2½ or 3-axis.

Other groups of material, apart from metals, for which AWJ can be of interest, include ceramics, and ceramics composites, polymer matrix composites, metal matrix composites and intermetallic materials. These types of materials are today cut industrially. However, several studies have indicated that more complex AWJ operations are of interest for these types of materials. For instance Hashish (1992) demonstrated the use of five consecutive operations, two cutting operations with an indexing rotation in between, a turning operation, a milling operation, and finally a drilling operation. Complex operations as milling and turning have been addressed by several researchers (Momber and Kovacevic, 1998).

Another type of cutting operation utilising a motion control with more than three axes is when using a fourth and fifth axis for an active control of the cutting edge taper and for increasing the effectiveness by a tilting the jet along the cutting path. These issues have been addressed by for instance Henning and Anders (1998), Knaupp and Meyer (2002) and Olsen et al (2003).

The use of six-axis robotics, or five-axis gantry equipment, can be found for instance in cutting of welding tapers of metal sheet. Another application for AWJ, as well as for pure waterjets, is cutting of formed composite shells. The use of five-axis gantry equipment has been addressed for instance by Alkire (1996). Kitamura et al (1992) reported of a 5-axis equipment dedicated to producing steam turbine components.

This study concentrates on cutting using a 4-axis motion control in which the fourth axis is a rotating axis, controlling the motion of the work-piece. Thus, the jet is still has a vertical direction. This type of motion control has for many cutting technologies, including abrasive waterjet machining, been used for machining of tubes. Operations then include making of holes and cutting-off of tubes. This study focuses on machining of bulk pieces of material.

2. TECHNOLOGY AND PROCESS FEATURES

2.1. Machine concept and control system

The basis of the machine used in this study is a 3-axis machine with a typical cutting table. The machine has been equipped with a 4th axis, for which the mechanics can be described as a lathe spindle. The rotational speed as well as the angle is controlled by the numerical control system. The machine’s z-axis is somewhat higher than in traditional machines, a feature which is an advantage in this context as relatively large pieces of materials can be cut when positioned in the spindle. The spindle is positioned approximately 100 mm above the level of the table. The concept is shown schematically in figure 1, along with the denotations of the axes. As the fourth axis is rotating around an axis linear with the y-axis, it is denoted the b-axis. The denotation is important to remember for the understanding of this paper.

The control system used is a digital system from Schneider Electric (NUM GP1050) and was adapted for the above mentioned configuration. The angle of rotation can be controlled simultaneously with the other three axes as well as separately. The rotational speed can be defined either by a given value, or, will be determined by the movement and speed of the linear axes.

Traditional AWJ machines are adapted to sheet metal cutting. The sizes of the cutting tables are configured for standard sheet sizes, and the working height is not larger than necessary. The use of a work-piece manipulation naturally calls for material formats other than sheet. In the paper can be seen examples of formats as circular rods, square rods and "undefined" bulk pieces. Interestingly enough, these types of formats are more common for such materials as ceramics, metal matrix composites and intermetallics. The work-piece can be fixtured using a chuck or other clamping devices. The requirements on the fixturing are not excessive with respect to forces, as the cutting forces are low. However, in certain cases of work-piece repositioning using high angular acceleration, higher forces may be in action. Further, the requirements of the fixturing can in some cases be relatively high with respect to geometrical accuracy. This especially is the case if the material has geometrical constraints or if the part needs to be repositioned in the chuck.

2.2. Process features for different types of manipulation

2.2.1 Indexing the part using the b-axis

This type of manipulation encompass cutting from two or more directions. Between each cutting cycle, the part is rotated a specific angle. After the last cycle the part is separated (cut off). Most simply there would be two cycles with a 90° rotation in between.

The first cutting cycle can be a 2-dimensional cutting, or in case of compensating for the shape of the work-piece, a 3-dimensional operation. The second cutting cycle can typically require a more difficult control of the z-axis as to compensate for a varying stand-off distance.

In figure 2 is shown a part machined in two cycles with a 90° rotation from an 18 mm cylindrical rod of steel. In the second cycle the stand-off is controlled, and thus the x, y and z are controlled simultaneously. The part presented has smooth geometrical features, which leads to a simple accessibility of the jet in the second cycle. In case the part angles are sharper or if the variations in the z-axis are larger, certain problems can be foreseen when trying to keep a small and constant stand-off. These issues are addressed in experimental test presented in paragraph 4.

2.2.2 Simultaneous control of the x, z and b-axis

This type of control enables cutting of more complex parts. A typical cutting cycle is most easily explained using an example. The part schematically shown in figure 3 would be rotated using the b-axis while simultaneously moving in x towards the tilted plane and simultaneously compensating the z-axis position, as can be seen in figure 4.

Also for this type of manipulation, several cutting cycles may follow. In paragraph 3 is presented an industrial case which includes several operations of this nature.

2.2.3 Simultaneous control of the x, y, z and b-axis

When simultaneously controlling the y- and b-axis, a single-curved surface is produced. The stylistic propeller shown in figure 5a depicts this type of control. In the first cycle, the basic curved shape of the propeller was cut. In the second cycle, the contours were cut while keeping a constant stand-off and angle to the previously cut surface. Other parts made controlling the y- and b-axis type are shown in figure 5b and 5c.

An interesting aspect of this type of manipulation is that the cutting speed will vary slightly along the cut height. The rotational speed will add a speed component in the x-direction as well as in the z-direction. The z-component will not add to the cutting speed as it is in the direction of the jet.

2.3. Manufacturing preparation

The syntax for simultaneously controlling all four axes typically has the following form in ISO-code;

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N100 G1 X10 Y100 Z15 B30 F60.
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The cutting head will move to the point x=10, y=100, z=15, at a speed of 60 mm/min while simultaneously rotating the work-piece to b=30°. A manual coding of single cutting cycles may be possible also when controlling more than 2 axes. One strategy that may be applied is a parametric syntax, in which one or more of the axes' values is set to be proportional to another axis' value.

However, when working with four axis and complex geometries, as well as when having several consecutive cutting cycles, a CAD/CAM solution will be necessary. For this reason a postprocessor for Pro/Engineer was developed for the presented machine configuration and control system. The postprocessor was mainly developed for the industrial case presented in paragraph 3. The postprocessor was developed using Pro/NC G-Post, in which the tool was considered to be a solid end mill with a diameter corresponding to the jet diameter.

3. MACHINING OF A COMPLEX PART

To demonstrate the potential use of the machine configuration, a complex geometry was cut. The part was a guide vane for an industrial gas turbine, and the material was a pressureless sintered $MoSi_2$ composite. This intermetallic material has a typical brittle-hard behavior. The study was made as a part of an industrial material development project. The objective was to test the machine concept, and also to test the machinability of the material. As the material is in a development stage, processes for near-net-shaping have not been developed. The AWJ cutting had the role of making the first rough machining, outgoing from a large piece of bulk material. Other machining technologies as HSM and EDM were tested on the material, but were found to have very low material removal rates. Diamond wheel grinding was tested and found to be suitable, but only for finishing operations.

Some of the cutting cycles are described in figure 6, and the result is shown in figure 7. The NC-code was generated using the postprocessor mentioned previously, and using a 3D solid geometrical model. The reasons why the geometry can be considered highly complex are:

- In total, eight cutting cycles were made on the part.
- In between each cycle, an indexing was made.
- In all the cutting cycles, the stand-off distance was controlled as to adapt to the geometry created in the previous cutting cycles.
- In several of the cutting cycles, the x, y, z and b-axis were controlled simultaneously.

4. EXPERIMENTAL TESTS

There are several limitations to the machine concept presented. One is that when having consecutive cutting cycles and varying geometrical features, it may be difficult to keep a low stand-off distance in the later cycles. The most obvious problem that may arise is the need to cut over a high 90° step.

These problems were addressed by experimentally testing three different strategies. The strategies are shown in figure 8 together with the result of the tests. The tests were made in aluminum, as to get evident results. The step shown is in this case considered to have been made in a previous cutting cycle and then having indexed the part 90°. The height of the step is 25 mm. A comment that can be made is that the cutting could be made from the opposite side to avoid the step. However, one could imagine parts with steps on both sides.

In the first strategy the nozzle movement is stopped in the y-direction at the step and the nozzle is moved in z at maximum speed. In the second strategy the nozzle continues at the set speed in y while moving in the z-direction. These two strategies give very large erosion of the part. The cutting width was is approximately 3 times the ordinary in the zone after the step.

Trying to overcome the problems associated with the first two strategies, a third was considered. In this strategy the cutting head is tilted when cutting over the step. Therefore a fifth axis would be necessary. To test this, the part was re-fixtured in the chuck and then the b-axis was used as being a fifth axis. The result was, as can be predicted, far better than the two previous strategies with respect to the geometrical error. The strategy could be simplified by using a constant angle during the cutting. However, as other geometrical features might be damaged by a tilted jet, or could need to be cut with a straight angle, a fifth axis would be advantageous.

5. DISCUSSION

It may be argued that complex cutting of this kind would be applied in dedicated equipments, cutting specific complex parts. This is believed to be only partly true. With comprehensive CAD/CAM software, the manufacturing preparation can be made relatively simply, and thus a machine of this type can be suited also for shorter series and prototyping. As mentioned previously, possible applications are foreseen in difficult to machine materials as ceramics, for which there is a lack of prototyping technologies.

An advantage of the machine concept presented is that it is mechanically relatively simple, and a machine can be made small and compact. Also, remember that the jet is still vertical, except for the lag, when the fourth axis is manipulating the work-piece. Another potential advantage concerns material removal. Since the cutting is in a bulk piece of material, it is appropriate to discuss the machining in terms of material removal. In for instance the case presented in paragraph 3, the cutting speed was very low, but the amount of material removed was very large. Altogether quite complex parts can be cut. The more axes that are controlled simultaneously, the more complex parts can be cut. The possibility to cut single-curved surfaces shows the flexibility of a small-diameter tool with this machine configuration.

There are several limitations of this machine concept. It is obviously not suited for very large work-pieces and especially not for sheet material. The lack of a fifth axis restricts the complexity of geometries that can be cut, and it also makes it difficult to cut over steps, as shown in the paper. Further, the dynamic properties of the jet are still a concern. The taper can be diminished by compensation, using the b-axis, but only in one direction. Another dynamic property of the jet is the lag, which redirects the jet in a backwards direction, which could damage the part being cut. Such a risk can be foreseen for instance in the case presented in figure 4. The lag may also cause a double-curved surface when simultaneously controlling the y- and b-axes.

Further work is needed in several areas. For example, the manufacturing preparation needs to be addressed in more detail. The post-processor for Pro/Engineer developed in this study must be developed further as to have better control over the dynamic properties of the jet. Another interesting topic is to integrate other machining methods as AWJ turning and possibly milling in this machine concept.

6. CONCLUSIONS

- Complex parts can be cut with a relatively simple and compact machine design using a 4-axis motion control, in which the fourth rotating axis controls the work-piece.
- CAD/CAM solutions are needed to fully utilize the potential of this concept.
- There are different levels of complexity possible when simultaneously controlling 2, 3 or 4 axes.
- When simultaneously controlling the rotating axis and moving along the parts axis, single-curved surfaces can be produced.
- There are limitations in this concept, including cutting over steps, which calls for the use of a fifth axis.

7. REFERENCES

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8. GRAPHICS

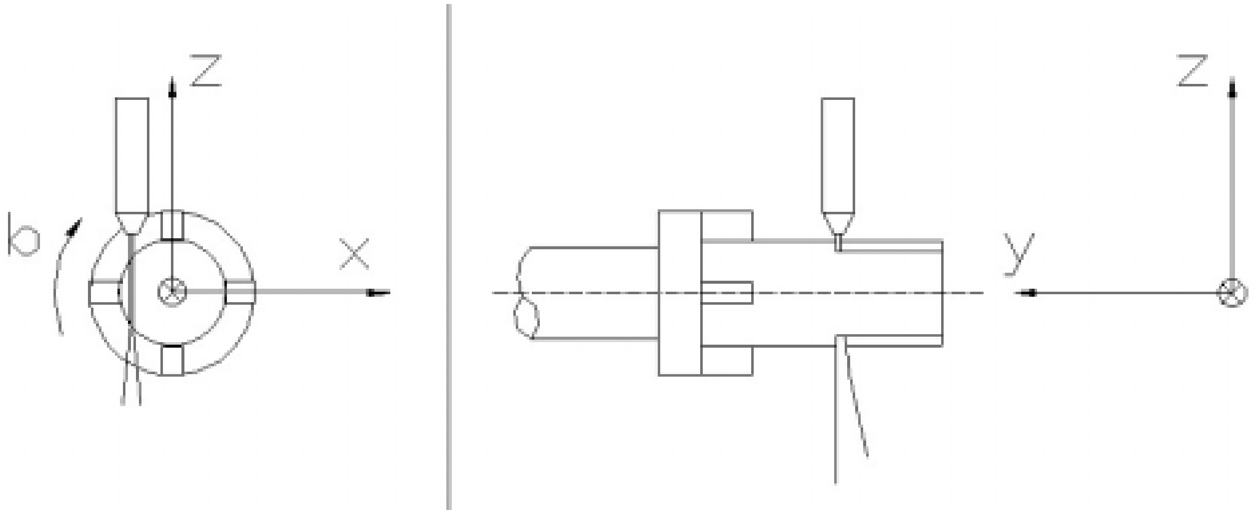


Figure 1. Machine configuration and definition of the 4 axes.

Figure 2. A complex part machined indexing the b-axis between two consecutive cutting cycles.

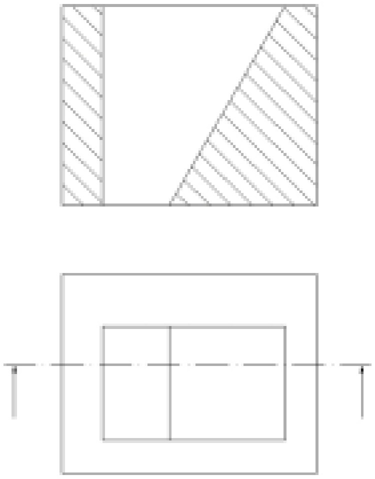


Figure 3. Schematic of a part cut with simultaneous control of the x, z and b-axis (figure 4).

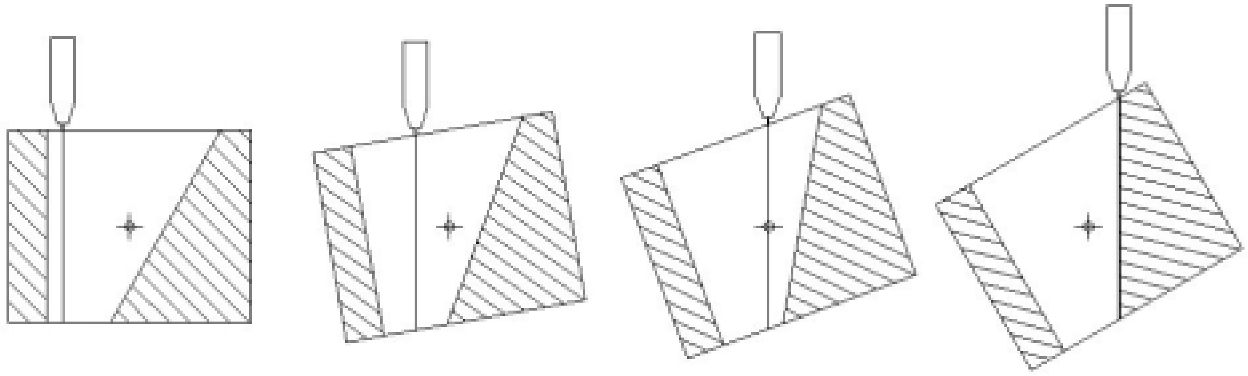


Figure 4. Simultaneous control of the x, z and b-axis for the part in figure 3.

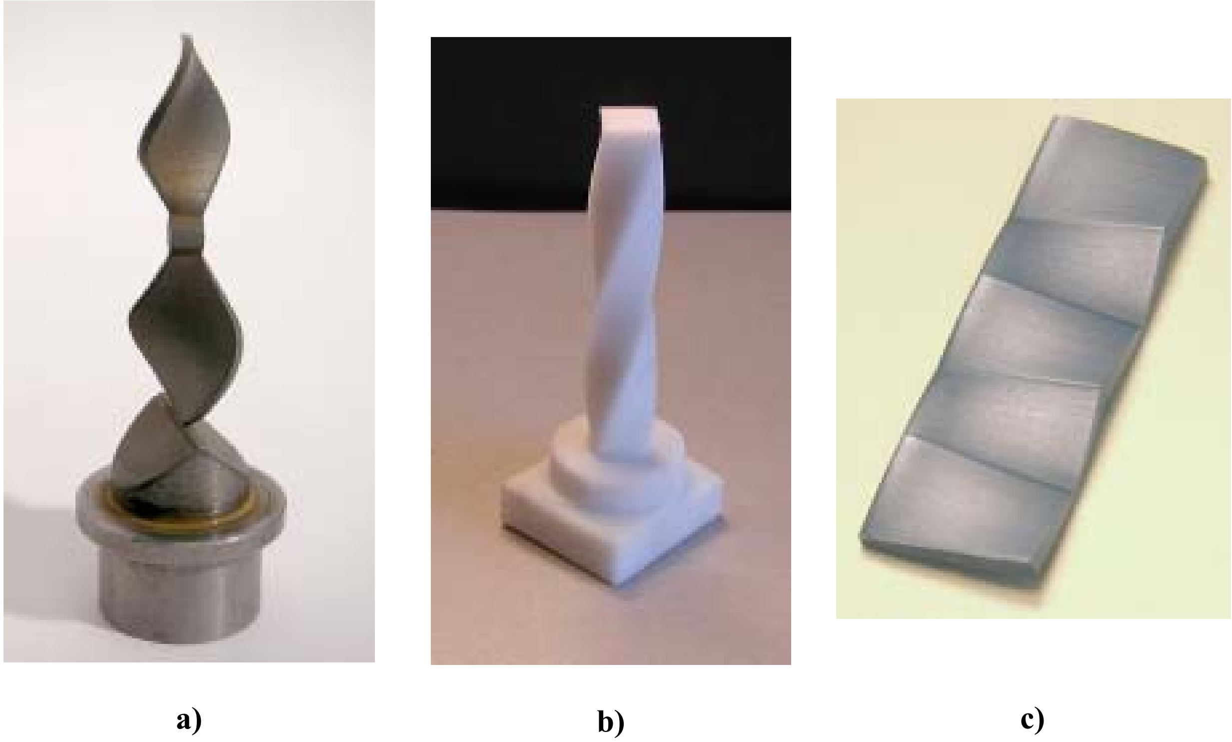
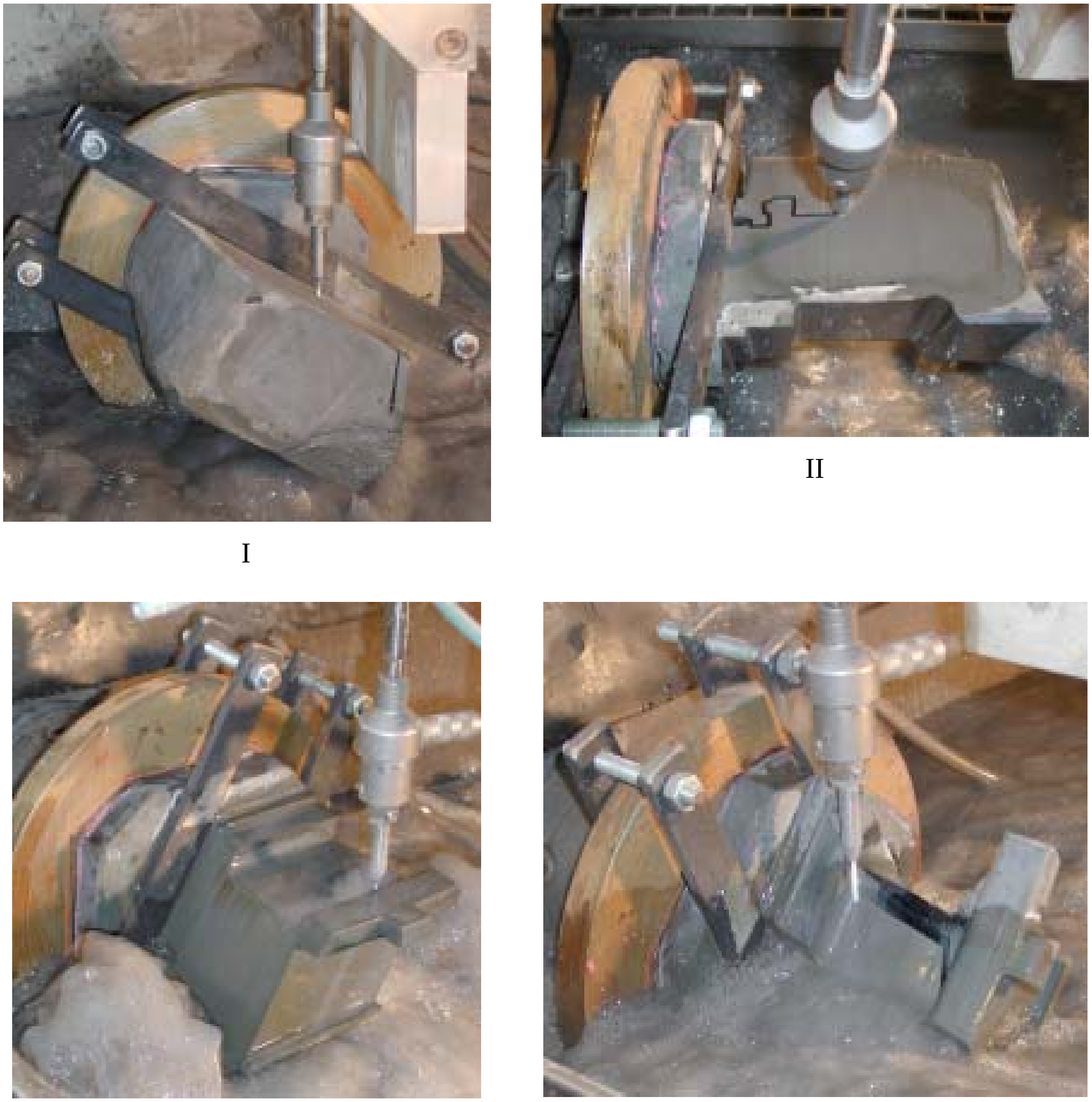


Figure 5. a) Part cut using simultaneous control of the x, y, z and b-axis
b) Simultaneous control of the y and b-axis and an intermediate indexing.
c) Simultaneous control of the y and b-axis



I

II

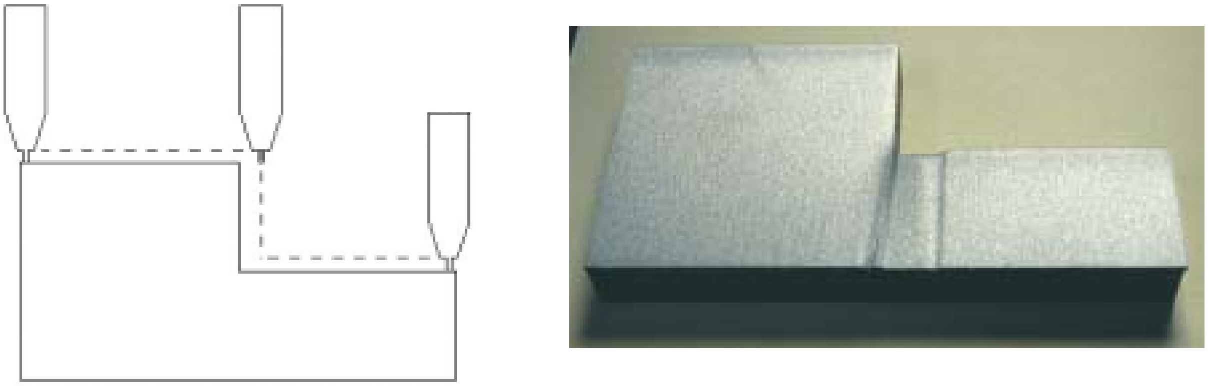
IV

V

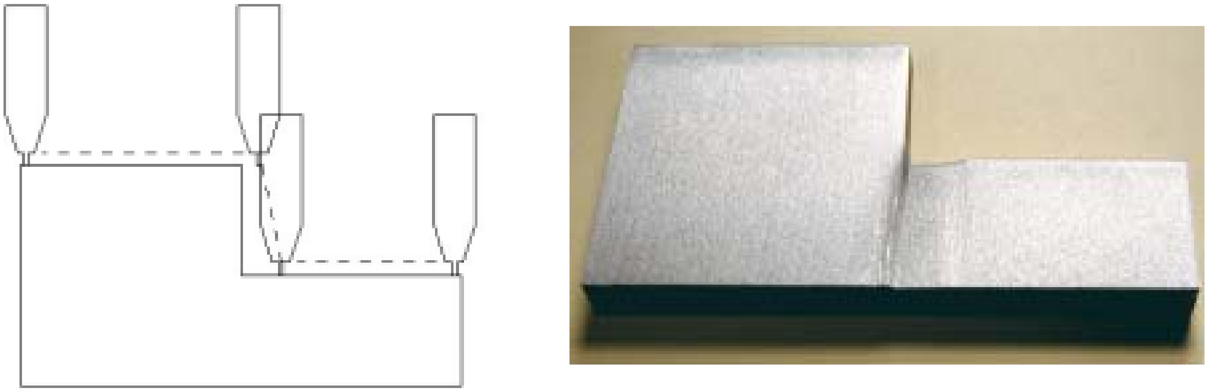
Figure 6. AWJ cutting of a complex part (guide vane) using simultaneous 4-axis control.

Figure 7. Finished rough machining of the guide vane using 4-axis AWJ cutting.

Strategy 1:



Strategy 2:



Strategy 3:

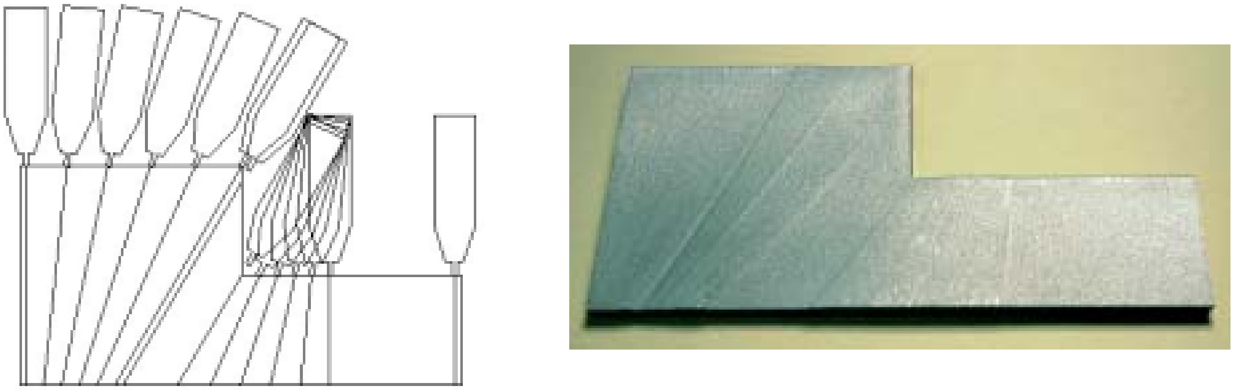


Figure 8. Strategies for cutting over steps (left), and test results in aluminum (right). The step height is 25 mm.