Study of Quality Parameters for Abrasive Waterjet Cutting of Metals

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1 Introduction

1.1 Evolution of Water Jet Cutting Method

Water has shaped nature with its eroding power for millions of years. Waterjet cutting has been used in the mining field since the end of the nineteenth century in Russia and New Zeeland (Engemann, 1993; Summers, 2003). In 1950, high-pressure water jets were used for woodcutting. In 1987, Mohamed Hashish was awarded the patent for "Method and apparatus for forming a high-velocity liquid abrasive jet", which is the basis for the current abrasive waterjet (AWJ) machining technologies (Hashish, 1987). Nowadays AWJ, a non-conventional machining technology, is used extensively in numerous industries for cutting various materials with low machinability, such as glass, ceramics, concrete, metals, composites, etc.

Abrasive waterjet machining uses the kinetic energy of a highly pressurized waterjet mixed with abrasive particles to produce a controlled erosion of the processed material in order to generate a cut along a contour (Hashish, 2015).

1.2 Advantages and Disadvantages

The main advantages of AWJ are:

- There is no heat generation, which is useful compared to other processing methods where the material has a heat affected zone where the mechanical and chemical

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properties are modified. The water quickly absorbs the heat resulting from the interaction between the abrasive particles and the material.
- Material loss is low due to the small width of the cut.
- There are no burrs and surface hardening.
- It can be used for processing various materials, even hard ones: stainless steel, titanium alloys, aluminum, brass, stone, granite, marble, ceramics, glass, plastics.
- No additional processing is required for finishing.
- CAD /CAM control leads to precision work.
- The cutting speed is high.
- The machining forces are small, and vibration is low.
- Intricate shapes can be obtained.
- Machine programming is simple and fast.

The main disadvantages of AWJ are:

- There is no possibility for simultaneous processing of multiple parts, which increases the costs.
- The equipment is expensive.
- The precision decreases for thicker parts due to the tailback and burr development.
- Water may oxidize metals or degrade some materials.
- There is a high level of noise during AWJ.
- It depends on water quality.

2 Background

The AWJ system is composed of the following main components (Fig. 1): water filtering subsystem, the ultrahigh pressure pumps, the cutting head, the motion system, the catcher tank, and the ancillaries.

2.1 Water Filtering Subsystem

As the waterjet may reach pressures up to 600 MPa and supersonic speeds up to 900 m/s, the water used in AWJ must meet the quality criteria presented in Table 1. Industrial waters may sometimes cause equipment to malfunction, due to the presence of solid particles. For example, if the concentration of calcium carbonate is too high, it can obstruct the cutting head, which is why several water treatment methods can be used. The simplest method uses resin filtering that replaces calcium salts with sodium salts. The second method is reverse osmosis, which removes the contaminants at the molecular level by forcing the water through a semipermeable membrane. The third method uses ionization, which replaces the negative ions (chlorides, sulphates) with positive, hydroxyl ions and sodium and calcium ions are replaced with hydrogen. It was observed that ionization is the most effective treatment to improve the service

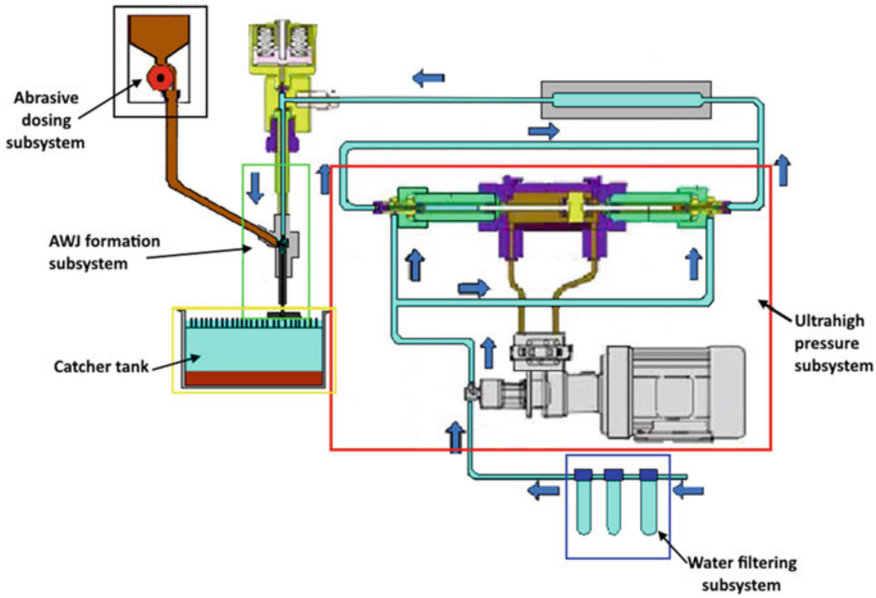


Fig. 1 AWJ system diagram

Table 1 Water requirements for AWJ

Attribute	Requirements
Total dissolved solids (TDS)	< 500 mg/l
Total hardness	< 25 mg/l
Fluorine	< 250 mg/l
Iron	< 2 mg/l
Manganese	< 1 mg/l
Turbidity	< 5 NTU
Free chlorine	< 1 mg/l
pH	6.5–7.5

life of the AWJ parts. Experiments have shown that reverse osmosis can enhance service life up to 190 h, whereas filtering may expand the service life with up to 78 h.

2.2 *Ultrahigh Pressure Subsystem*

This is used to increase water pressure from the ambient value to the high values necessary in the process using multistage pumps. High pressure values require the use of hydraulic pressure intensifiers from where the water passes into an attenuator

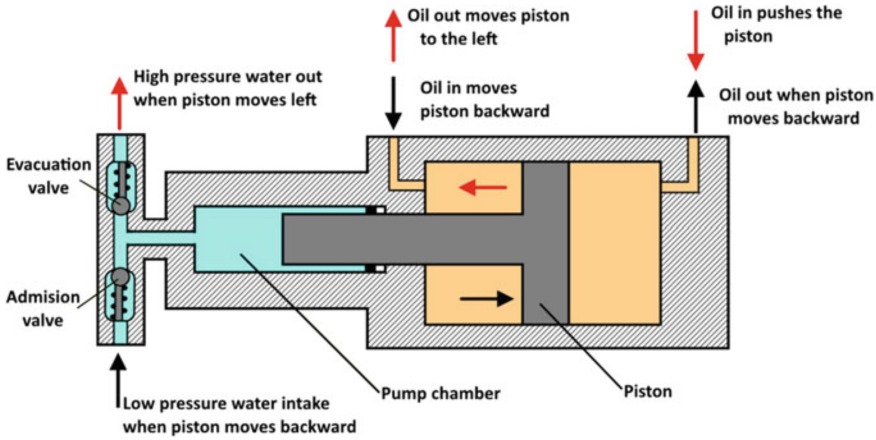


Fig. 2 Pressure multiplier

to reduce the influence of the cyclic pressure variations determined by the intensifier functioning. The intensifier is made of two cylinders with diameter ratios from 1/10 to 1/25. On the larger side, the pressure on the hydraulic plunger is 5–35 MPa and because of the diameter ratio, in the second cylinder the pressure can rise to 400 MPa (Fig. 2). To assure a continuous functioning, two or more pressure intensifiers can be coupled in parallel (Fig. 3).

2.3 Jet Formation Subsystem

(a) **Waterjet**. Waterjet cutting principle is based on the effects of a thin jet of water has upon a material at high pressure and high flowing speed. Waterjet cutting is considered a form of micro erosion. During this process, a large volume of water is forced through a small diameter nozzle. The constant high pressure water flow interacts with a small area of the material causing micro-cracks at the impact. The water removes the detached particles, so the micro-cracks are exposed to erosion and propagate until a full cut is obtained. The system used for the formation of the waterjet is presented in Fig. 4. An important aspect is the coherency of the waterjet. The structure of the waterjet contains an initial coherent flow which gradually spreads and turns into droplets. A more coherent waterjet packs an increased power density, so it is more efficient.

(b) **Abrasive waterjet**. Cutting is achieved using a waterjet mixed with an abrasive material. The mixing and homogenization take place in the mixing chamber of the cutting head and the kinetic energy is transferred in the focalization tube (Fig. 5). AWJ can be used to cut a large variety of materials, following various contour shapes, as an alternative to other technologies, such as laser or plasma cutting.

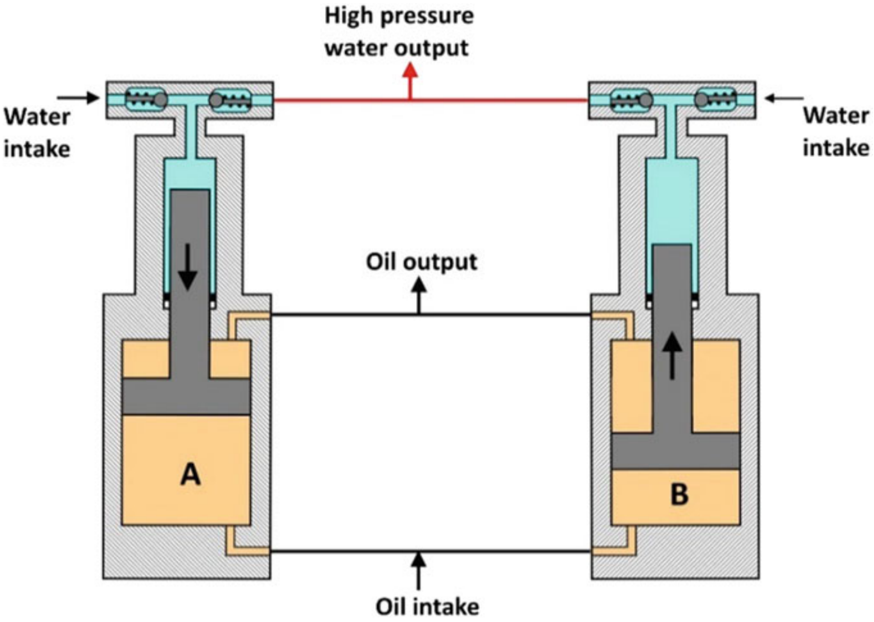
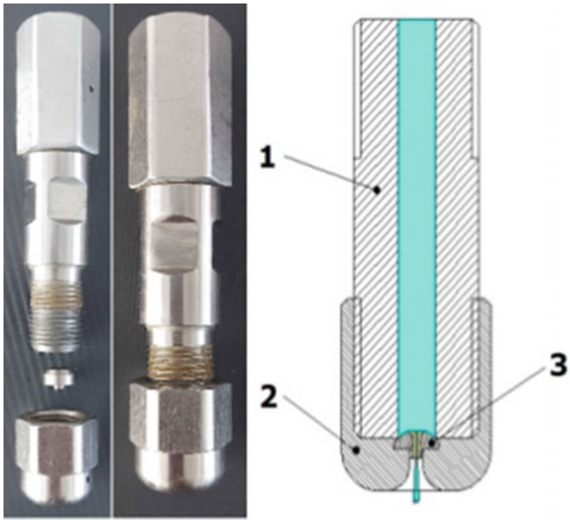


Fig. 3 Parallel pressure multipliers

Fig. 4 Waterjet cutting head: high pressure tube (1), clamping nut (2), nozzle (3)



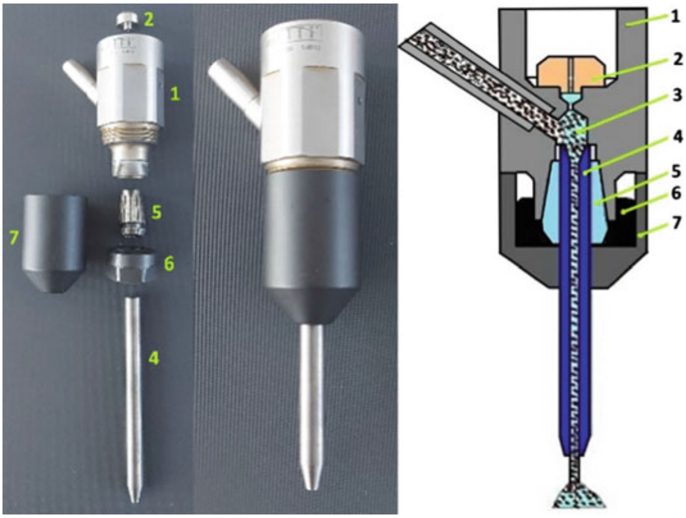


Fig. 5 Abrasive waterjet cutting head: casing (1); nozzle (2), mixing chamber (3), focalization tube (4), collet (5), clamping nut (6), protective case (7)

2.4 The Catcher Tank

This is used to collect the mixture of water, abrasive particles, and processed material because only 10% of the total jet energy is consumed during cutting. The rest of the energy is absorbed by a container (tank) that may use different construction solutions: a bed of 0.15–0.3 m thick made of steel or ceramic balls (Fig. 6a), a layer of water 0.5–1 m deep (Fig. 6b), or plates made of corrosive resistant materials (Fig. 6c).

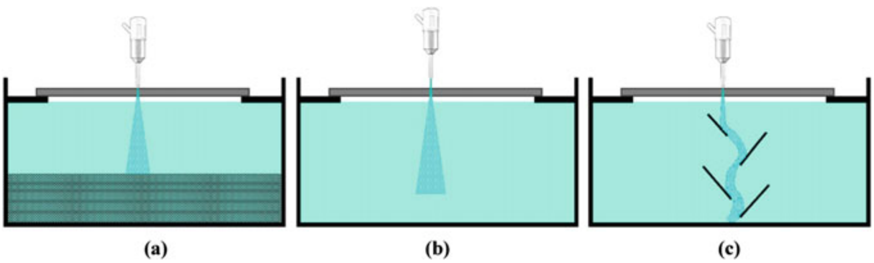


Fig. 6 Jet energy amortization system

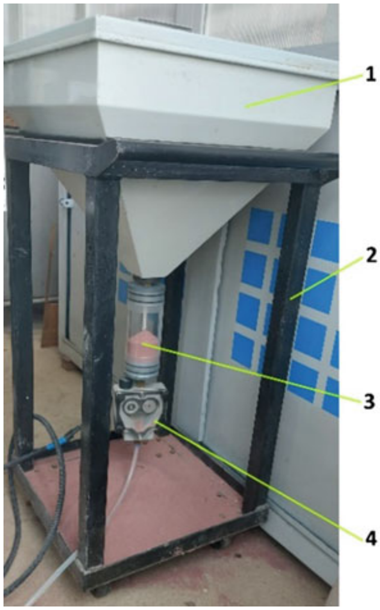


Fig. 7 Abrasive dosing: hopper (1), hopper stand (2), control cylinder (3), dispenser (4)

2.5 Abrasive Material Dosing System

The abrasive material dosing system is composed of a hopper and a metering valve. This valve measures and controls the abrasive flow, with possibility to set values within an interval of 1–999 g/min. It is recommended that the distance between the dosing system and the cutting head should be minimum. The dosing system has the following components: the hopper where the abrasive material is contained, a control cylinder to see when the abrasive runs out, and the dispenser that is connected to the numerical controller (Fig. 7).

2.6 The Motion System

The motion system is used to control the position of the cutting head, which is necessary to perform the cutting. CAD/CAM software and CNC controllers are used to create the paths and to interpolate the motion of the machine.

Table 2 Abrasive materials and hardness properties

Abrasive material	Hardness	
	Mohs	Knoop
Aluminum oxide	8–9	2.100
Garnet	7.5	1.350
Fine granite particles	8	–
Olivine	5.5	1.100
Silicon carbide	9.15	2.500
Sand	–	700
Granulated steel	–	400–800
Copper slag	–	1.050
Glass powder	5.5	400–600
Zirconium	–	1.300

Fig. 8 Microscope image of garnet abrasive particles

2.7 Abrasive Materials Utilized for AWJ

AWJ uses various types of abrasive materials, such as: aluminum oxide, garnet, glass, fine particles of granite, silicon carbide, sand, steel beads, copper slag aggregate, olivine, etc. Abrasive materials are classified using criteria such as hardness, structure, shape, grain dimensions. Table 2 presents the most used materials and their hardness.

A microscopic image of garnet granules is presented in Fig. 8 and the material properties are in Table 3.

2.8 Kerf Geometry

According to ISO/TC 44 N 1770 standard (2010), kerf geometry is characterized by the following parameters (Fig. 9):

- Li—entrance width of cut

Table 3 Abrasive material properties—garnet produced by Barton International (Barton.com, 2023)

Properties	Observations
General description	– Combination of almandine $Fe_3Al_2(SiO_4)_3$ and pyrope $Mg_3Al_2(SiO_4)_3$ (silicates) – Homogenous minerals – No chemical emissions – Aluminum and iron ions may be partially replaced by calcium, magnesium and manganese: $Ca_3Fe_2(SiO_4)_3$, $Mn_3Al_2(SiO_4)_3$
Chemical composition	– Silica (SiO_2) 41.34% – Ferrous oxide (FeO) 9.72% – Ferric oxide (Fe_2O_3) 12.55% – Aluminum oxide (Al_2O_3) 20.36% – Calcium oxide (CaO) 2.97% – Magnesium oxide (MgO) 12.35% – Manganese oxide (MnO) 0.85%
Hardness	7–9 on Mohs scale
Power	Hard to break
Granules shape	Sharp edges with irregular shape
Splitting (cleavage)	Pronounced lamination, the cleavage plane is irregular
Color	Rose red
Stripes	White
Transparence	Transparent
Gloss	Vitreous
Specific gravity	3.9–4.1 g/cm^3
Refractive index	1.83
Facet angle	37° and 42°
Crystallization	Cubic (isometric) rhombic dodecahedron, tetragonal or combinations
Melting temperature	1315 °C
Magnetism	Variable magnetic attraction
Moisture absorption	Inert, nonhygroscopic
Pathologic effect	No
Harmful emissions	No

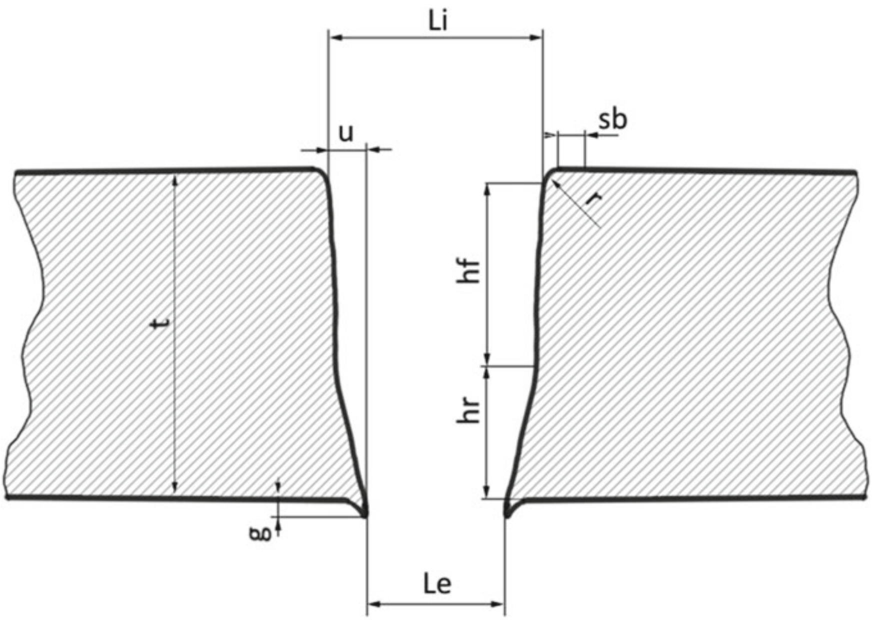


Fig. 9 Terms defining kerf geometry

- Le—exit width of cut
- g—burr
- hf—fine cut
- hr—remaining surface
- u—perpendicularity
- r—edge radius
- sb—beam affected zone
- t—workpiece thickness.

2.9 AWJ Process Parameters

AWJ process is controlled by a series of input parameters that can be classified into the following categories: hydraulic parameters, cutting parameters, abrasive parameters, material parameters, mixing parameters (Jegaraj & Babu, 2005; Natarajan et al., 2020; Sisodia et al., 2023).

The hydraulic parameters refer to:

- *Water jet pressure*. This gives the kinetic energy necessary to cut through the material. The depth of jet penetration is directly proportional to the pressure. It

was also observed that higher pressure improves surface quality and reduces water and abrasive consumption.
- *Nozzle diameter*. The depth and width of the cut are dependent on the nozzle diameter. Larger nozzle diameters increase the depth of the penetration and the width of the cut, also.

The abrasive parameters refer to:

- *Abrasive flow rate*. The rise of the abrasive flow rate increases the depth of jet penetration to a certain extent. However, it was observed that overdosing of the abrasive leads to an agglomeration of the mixing chamber that decreases the abrasive kinetic energy. The optimum amount of abrasive material depends upon the water jet pressure, nozzle diameter, the length and inner diameter of the focalization tube.
- *Abrasive material*. Various materials are used, as mentioned earlier, but garnet is the most common.
- *Abrasive particles sizes and shapes*. The size of the abrasive particles (mesh number) reflects on the removal speed. A smaller mesh number means that the abrasive has a larger granule size and higher removal speed. This is also associated with higher surface roughness. Medium and smaller grains (#60 to #200) are used for cutting metal, glass, or composite materials.

The mixing parameters refer to the *focalization tube length* and *inner diameter*. The jet coherency is improved when the tube dimensions increase to a critical size. The depth of the jet penetration improves when the tube length is increased, as the abrasive particles require a certain acceleration distance. However, if the length is too high, the friction between the tube walls and the abrasive particles can lower the speed, thus reducing the AWJ efficiency. Usually, the length to diameter ratio varies from 50 to 100. The inner diameter of the focusing tube has a similar influence. The inner diameter varies in the 0.5–1.3 mm range, while the length is up to 150 mm. A ratio of 3:1 between the tube inner diameter and the nozzle diameter is recommended (Hashish, 2015).

The cutting parameters refer to:

- *Standoff distance*. This is the distance between the nozzle and the upper surface of the processed part. A higher standoff distance will reduce the depth of the cut, increase surface roughness and the kerf taper. Larger standoff distances can be used when the water jet is more coherent. Typically, the standoff distance varies between 1 and 5 mm.
- *Traverse speed*. This is the relative speed between the cutting head and the part. Lower traverse speeds are associated with a higher quality of the cut because of the more intense interaction between the AWJ and the material. Higher traverse speeds lead to reduced penetration of the jet, with higher surface roughness and increased kerf taper.

- *Inclination angle*. This is the angle between the part surface and the flow direction of the AWJ and can by modified by tilting the cutting head. It can be used in the machining of soft, fragile materials, or to affect the kerf taper formation.

3 Objectives

The current paperwork has the following objectives:

- Acquire by the students of general notions related to AWJ.
- Capacity to use the equipment and the programming software.
- Development of skills concerning:
  - AWJ process planning—realization of part contour, choosing the process parameters, resource planning, machine programming, choosing of the quality parameters.
  - Conducting the experimental test.
  - Checking of the parts.
  - Drawing conclusions.

4 Resources and Organization

4.1 AWJ Machine

The AWJ cutting machine used in the experimental study is KNUTH Hydro-Jet Eco 0615 with the main technical features as follows: the cutting range 1510 × 610 mm; operating pressure 1500 bar; water jet cutting mode without and with abrasive mix; displacement mode on X and Y axis—automatically, on the Z axis—manually; maximum feed rate 4 m/min; displacement precision on X axis ± 0.03/300 mm; displacement precision on Y axis ± 0.02/300 mm; repeatability on x axis ± 0.02/300 mm; repeatability on y axis ± 0.02/300 mm; motor power 7.5 kW; water flow 2.4 l/min.

The machine is composed of the following main units (Fig. 10):

- The water tank (1) and the cutting head (2) (Fig. 10a).
- The water pressure system (3) (Fig. 10b).
- The dosing system (Fig. 10c).
- The control and command unit contains the NC controller, the hand panel, and the wheel panel (Fig. 10d).

The hand panel contains the buttons for interacting with the NC command and two potentiometers to override the technological parameters (traverse speed, waterjet pressure) (Fig. 11).

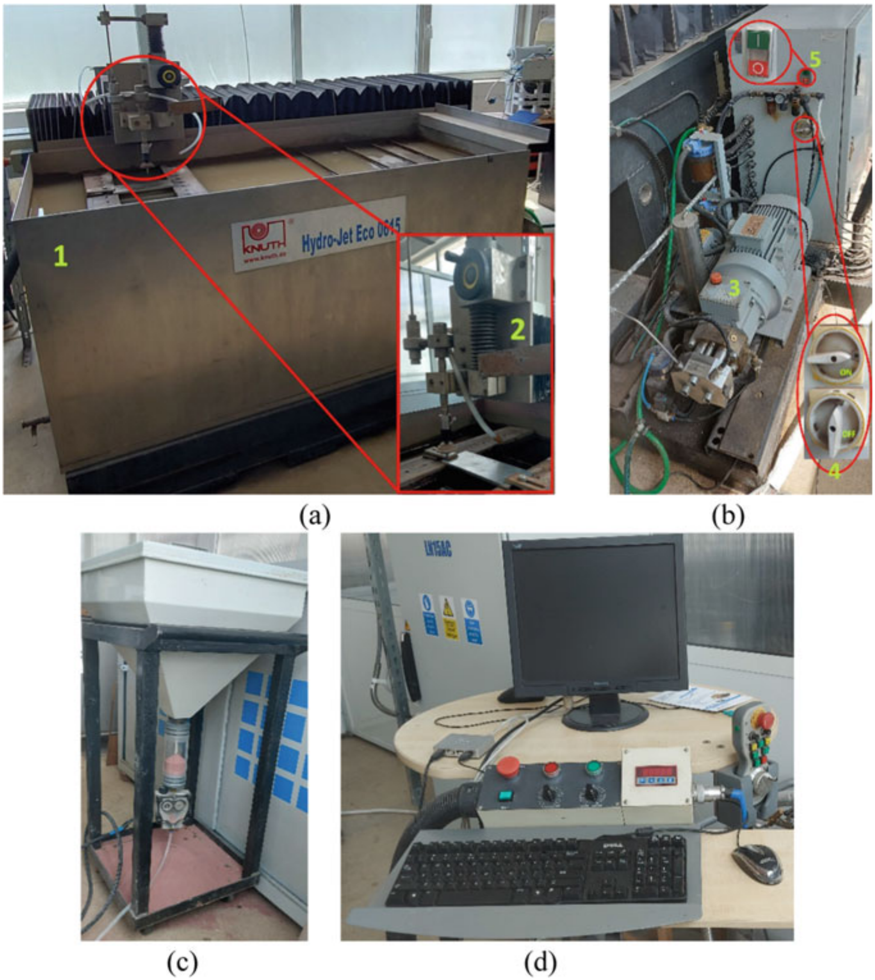


Fig. 10 AWJ cutting machine: water tank and the cutting head (**a**), ultra high-pressure pump and powering buttons (**b**), abrasive dosing (**c**), machine control and command (**d**)

The handwheel is used for the manual operation of the machine and contains the following elements (Fig. 12): the wheel for the manual displacements (1), NC Start button (2), NC Stop button (3), Jog− minus direction (4), Jog+ positive direction (5), Sand button to start abrasive flow (6), Pump button to start up the pressure pump (7), Pressure button to start the high pressure pump (8), axis selection switch (9), position increment switch (10), Emergency stop button (11), handwheel enable switch (12) on both sides.

Fig. 11 Machine hand panel: Emergency button (1), NC stop (2), NC start (3), Reset (4), Feed rate override (5), Pressure override (6), High pressure display (7)

Fig. 12 Machine handwheel

4.2 Material Processed

The part was cut from a 200 × 70 × 6 mm aluminum alloy plate (Fig. 13). Al6061-T651 is a widely used aluminum alloy due to its general characteristics, such as a very good strength-to-weight ratio, good machinability and weldability, high corrosion resistance, and heat treatability. Anodization gives a protective layer for finished parts. Its applications are various and include aeronautical components, couplings, marine fittings and hardware, electrical connectors and components, hydraulic pistons, valves, appliance fittings, decorative hardware, camera parts, bike frames, etc. Chemical composition of Al6061-T651 is presented in Table 4, while mechanical properties are in Table 5.

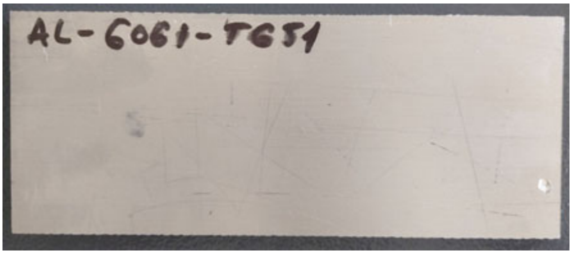


Fig. 13 Aluminum alloy plate

4.3 The Part

The part chosen for this work combines the most often used geometrical features to exemplify the use of AWJ technology for cutting exterior and interior contours. The part contains straight and circular edges to form the exterior shape whereas the interior contour is a circle (Fig. 14).

5 Session Development

5.1 Turn On/Off the AWJ Cutting Machine

The procedure to turn on/off the AWJ cutting machine is described in the diagram from Fig. 15.

5.2 Job Creation

The AWJ cutting procedure, or the job as denoted by the software, can be divided into two main sections. The first section contains the steps necessary to create the numerical program that the machine uses to cut the contour of the part, whereas the second section contains the steps for the actual AWJ cutting using the NC code.

The software used to set up and control the machine is PACut (Fig. 16a). At the start, the initial screen of the program (Fig. 16b) displays some general information, and the user must click the ***PACut*** button from the right-side, which opens a new window with the job options (Fig. 17).

The job option window contains three choices:

- New job is used for the creation of a new AWJ cutting project.
- Job list is the database that contains previous AWJ cutting programs, which can be reused or edited.
- Exit when the user wants to quit the program.

Table 4 Chemical composition of Al6061-T651

Element	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Others, each	Others, total
%	95.8–98.6	0.04–0.35	0.15–0.4	Max 0.7	0.8–1.2	Max 0.15	0.4–0.8	Max 0.15	Max 0.25	Max 0.05	Max 0.15

Table 5 Mechanical properties of Al6061-T651

Brinell hardness	Elasticity	Yield strength	Ultimate tensile strength	Elongation at break
95	68.9 GPa	276 MPa	310 MPa	17%

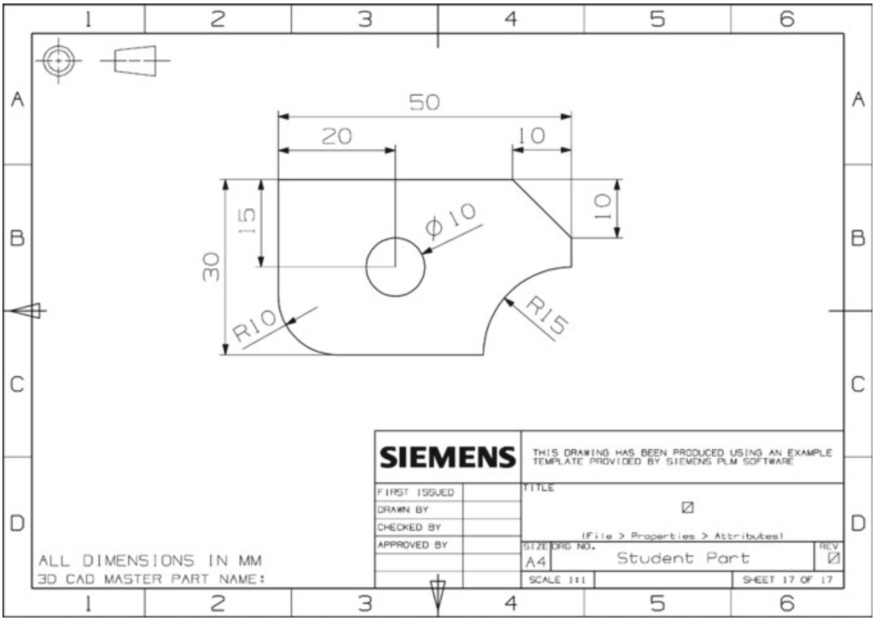


Fig. 14 Part drawing

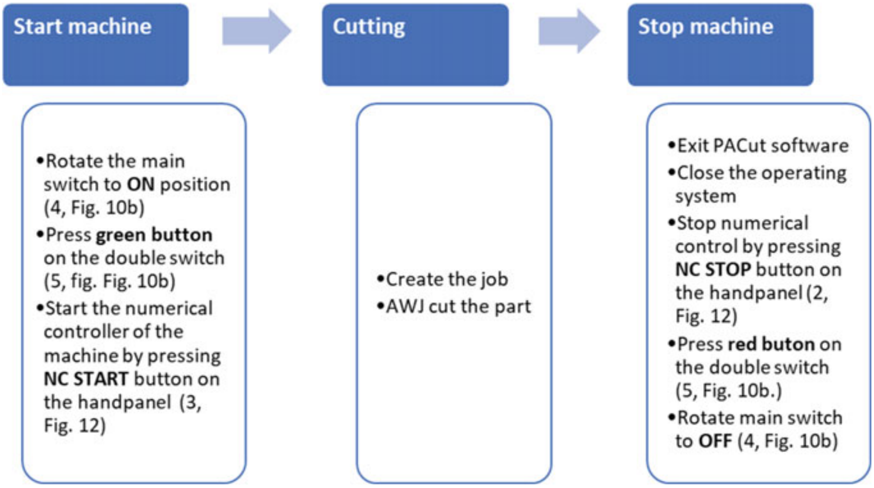
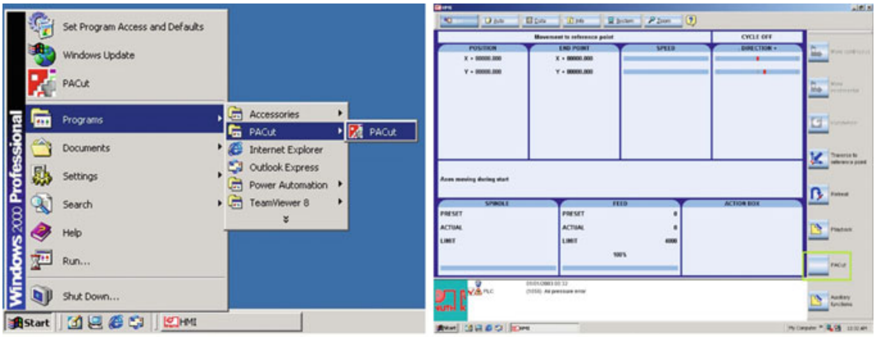


Fig. 15 AWJ cutting machine power on/off procedure



(a) (b)

Fig. 16 Program start (**a**), start screen (**b**)

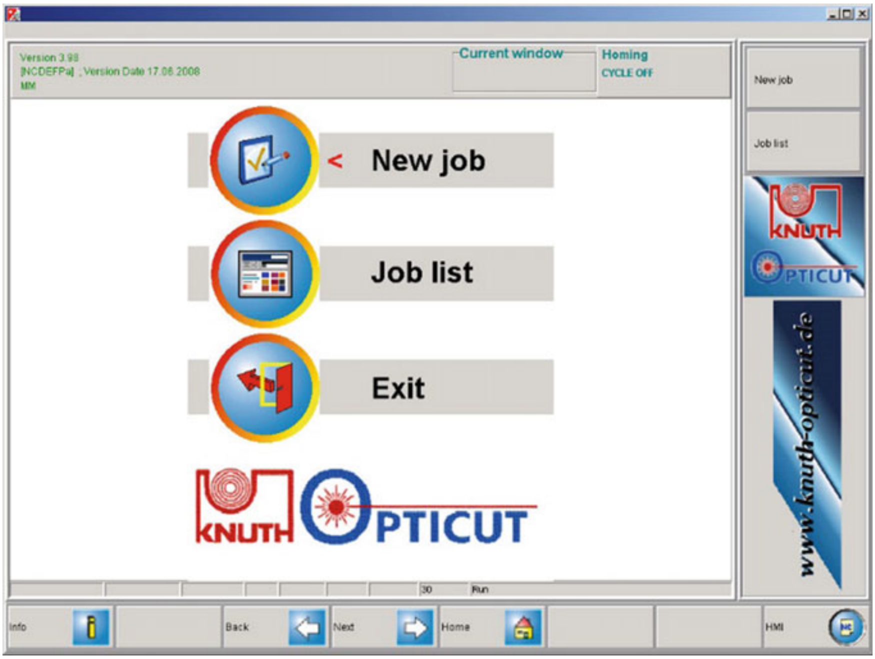


Fig. 17 Job options

For the current work a new job must be created, which opens the interface related to the sheet database (Fig. 18). The sheet database contains inputs from previous works, while also allowing the user the possibility to create new ones. Next, a new sheet is defined by clicking the button *6 New database entry* from the right-side panel. In the newly opened window (Fig. 19) the user must provide the following information:

- The material field in which the user specifies the material that the part is made of. The current job is carried out using an aluminum alloy Al6061.
- The thickness field in which the user must specify the thickness of the part to be cut. For this job the part will be cut from a plate with a 6 mm thickness.
- Width and height are used to provide the dimensions of the plate used to cut the part from. The plate for this job is 70 × 200 mm.
- Speed is used to specify the value of the cutting head speed, also known as the traverse speed. For the current project, the value of the traverse speed is 50 mm/min.
- Cutting path offset is the distance between the jet axis (focalization tube axis) and the theoretical contour of the part. The value of the offset is a little larger than the radius of the focalization tube internal hole to take into consideration the spread of the jet, so the value was set to 0.6 mm.
- Number of sheets refers to the number of sheets stacked together when one wants to manufacture multiple parts with only one cut. This number is limited by the sheet thickness and the risk that the jet does not penetrate through the entire thickness of the stack. For the current job a single plate is used, therefore the value of the number of sheets is 1.

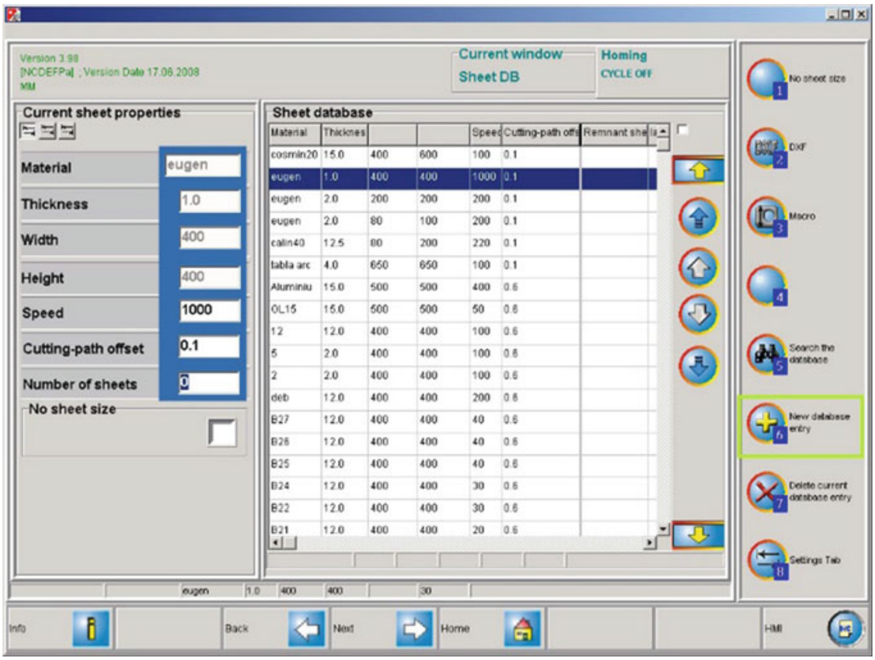


Fig. 18 Sheet database interface

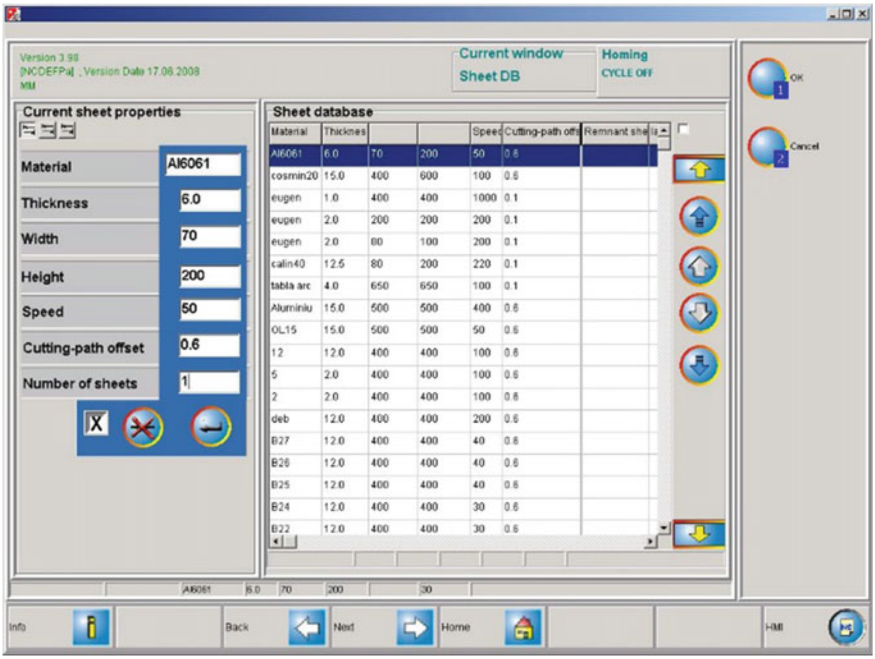


Fig. 19 Creation of a new sheet for the job

Next step of the setup process is to choose the technological parameters, which are accessed by clicking on the third button in the Current sheet properties. In the program interface, the user must introduce values for the following parameters (Fig. 20):

- Abrasive is working as a logical operator with two values: 0 when the cutting is executed only with pressured water, without abrasive, and 1 when the cutting is done with AWJ. For the current job, the parameter is set to 1, since metal cutting requires the use of abrasive material.
- Low pressure sets the minimum pressure of the water jet. For this job, the value is set at 1500 bar.
- Piercing pressure sets the value of the water jet pressure during the initial penetration in the material. For this job, the value is set also at 1500 bar.
- Piercing time sets the time interval used by the AWJ to cut the initial penetration hole into the material. For the current job, the time was set at 8 s.
- Piercing diameter is the diameter of the piercing hole, which was set at 1 mm.
- Cutting pressure sets the pressure of the water jet during the cutting process. For superior cutting quality, this value was set at 1500 bar.
- Sand value sets the value for the abrasive flow rate. In the current job, this parameter was set at 300 g.

To save the values of the parameters, click on the *Save ramp* button (Fig. 20). Next, click on the button *Make a new database entry* to add the newly defined material

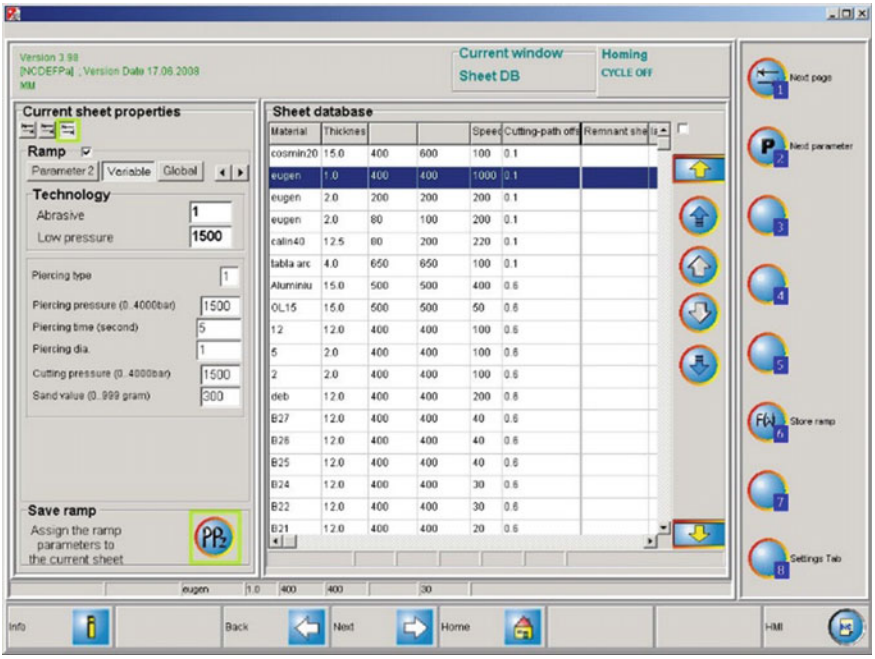


Fig. 20 Technological parameters

to the existing database. After that, the user must click the button *Next* situated at the base of the screen to pass to the subsequent step where the geometry of the cutting contour is defined (Fig. 21).

There are two ways to define the cutting contour, which represents the shape of the part. The first one is to use the drawing module of the PACut software. The second one is to design the part using an external dedicated CAD software and export it to a dxf format file that can be imported afterwards in PACut.

This second way is used to further define the cutting contour into the job. For this, the user must click the button *6 Load DXF file from disk* (Fig. 22) that opens a navigation window to the desired dxf file (Fig. 23). Opening the file brings the contour into the software and the user must click the button *Next* to set up the tailoring of the contour on the sheet or the plate from which the part is cut. The cutting may be executed either on external or internal contours with various shapes, such as polygonal, circular, or combined. The cutting must start and end at certain distances from the contour (lead in and lead out) to avoid damaging the shape of the part.

Using this interface (Fig. 24) the user can set the following parameters:

- The orientation angle defines the angular position between the contour and the plate. Depending on its shape and dimensions, contour rotation can ensure a higher degree of material usage.

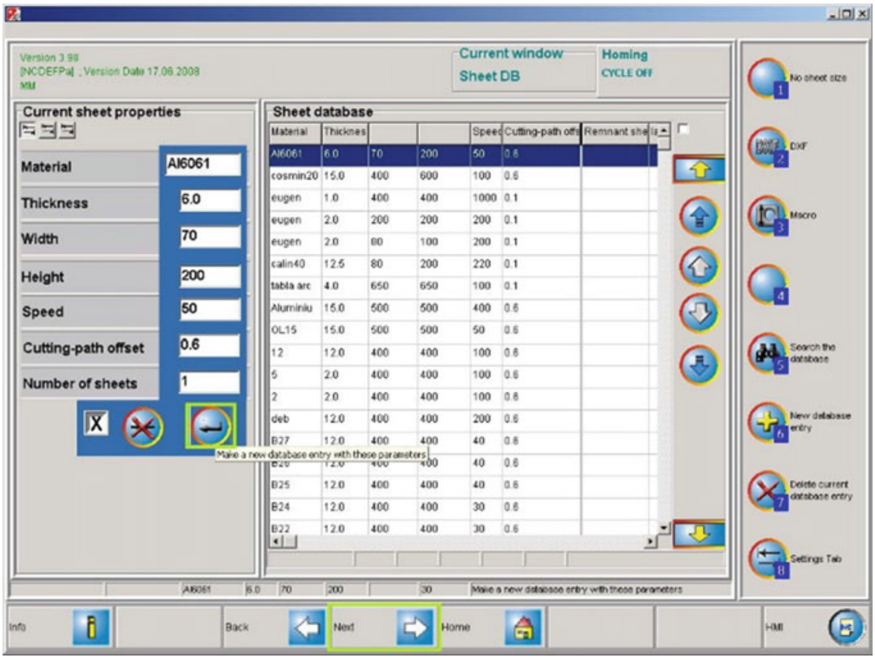


Fig. 21 Adding the material in the database

- The lead-in and lead-out size, which defines the length of the paths of the cutting head at the beginning (green arrow representation) and at the end of the cutting (red arrow representation), respectively, when external contours are executed. For the current job, the lead-in (entrance distance) was set at 3 mm, while the lead-out (exit distance) is 2 mm.
- For the internal circular contour, similar values were assigned to the lead-in distance (3 mm) and the lead-out distance (2 mm) of the cut.
- There are various strategies to approach the beginning and the end of the cutting paths: either straight, or tangential to the contour.

After clicking the button *Next*, a new interface opens. If multiple parts are to be cut from the sheet, the user can define a matrix of contour distribution with the desired number of lines and columns. For the current job only one part is cut, as represented in Fig. 25. In addition, in this interface the NC code is saved with an assigned name (*StudentPart*) by clicking button *1 Save NC program to job list*.

This concludes the first section of the AWJ cutting procedure.

The subsequent steps are related to the second section of the process, where the NC program is loaded into the machine controller and the part is cut out using the AWJ.

Thus, the next step is to find the NC program in the Job list (Fig. 17). There are two possibilities, one is by scrolling the list, the other is to use the Search function.

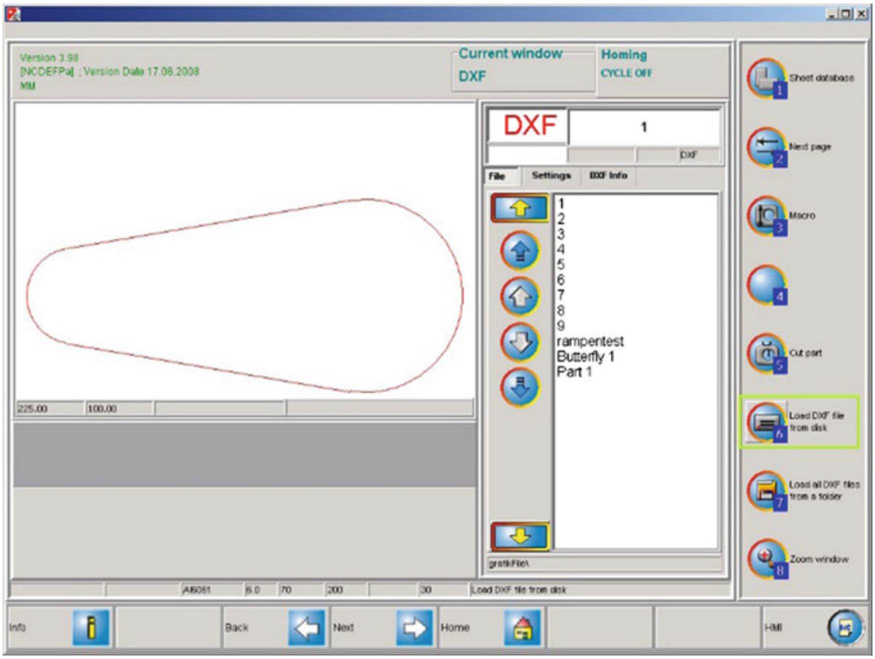


Fig. 22 Definition of the cutting contour

After the program loads, the main characteristics are displayed on screen (Fig. 26). Click the button *Next* to enter the cutting program.

The interface displays the contour of the part together with the lead in and lead out distances. It is necessary to set the point of origin for the path of the cutting head: click *5 Manual* button (Fig. 27a), then *1 Move machine button* (Fig. 27b) to establish the position of the origin point. The coordinates of the origin point must be introduced and after that click on *4 Shown position = start position button*, then *6 Move machine to start point* button (Fig. 28). On the machine handwheel click on the *START* button to move the cutting head in the machine origin point. After another click on the *START* button from the handwheel to move the cutting head in the starting position for cutting (Fig. 12). Click *Back* button to return to the previous screen. The standoff distance is set manually to 3 mm by using a gauge block (Fig. 29). Press the *Start cutting* button (Fig. 27a) and then *START* button on the handwheel and the machine will start cutting the programmed contour (Fig. 30).

During the operation, the position of the cutting head can be followed in real time on the screen (Fig. 31).

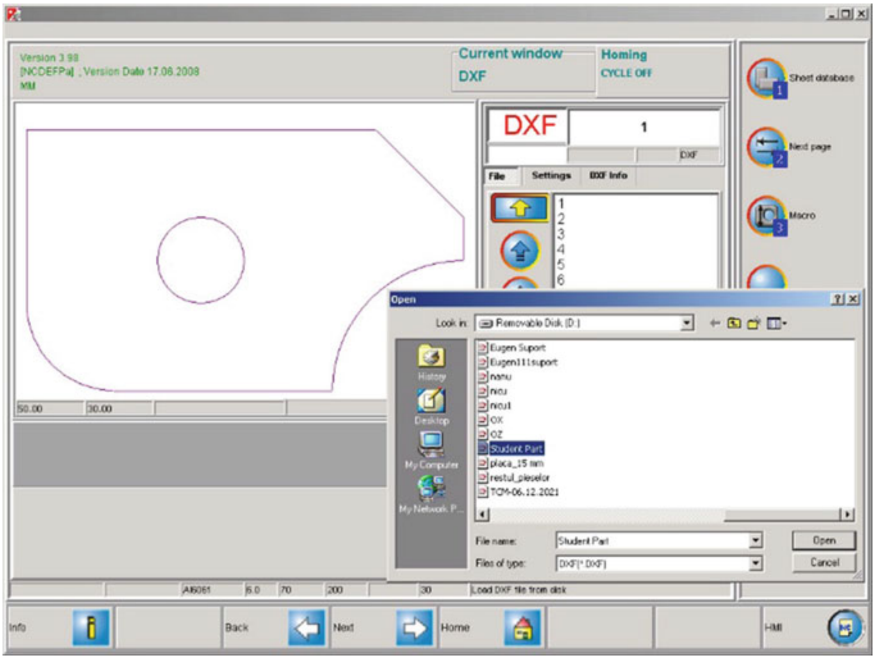


Fig. 23 Import the contour from the dxf file

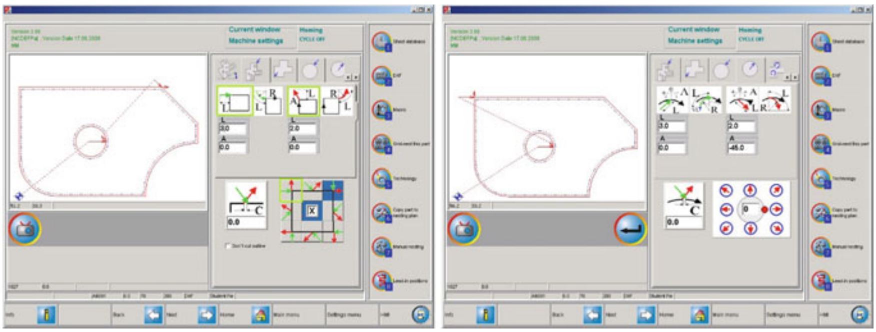


Fig. 24 Setting of the cutting path

6 Outcomes

The part obtained from the AWJ cutting process is presented in Fig. 32.

The quality of the part is assessed by examining the following elements: dimensional accuracy, contour defects, kerf angle, and kerf surface aspect.

The dimensions of the part can be measured using various instruments but, for this work, a profile projector was chosen. Profile projectors, also known as optical

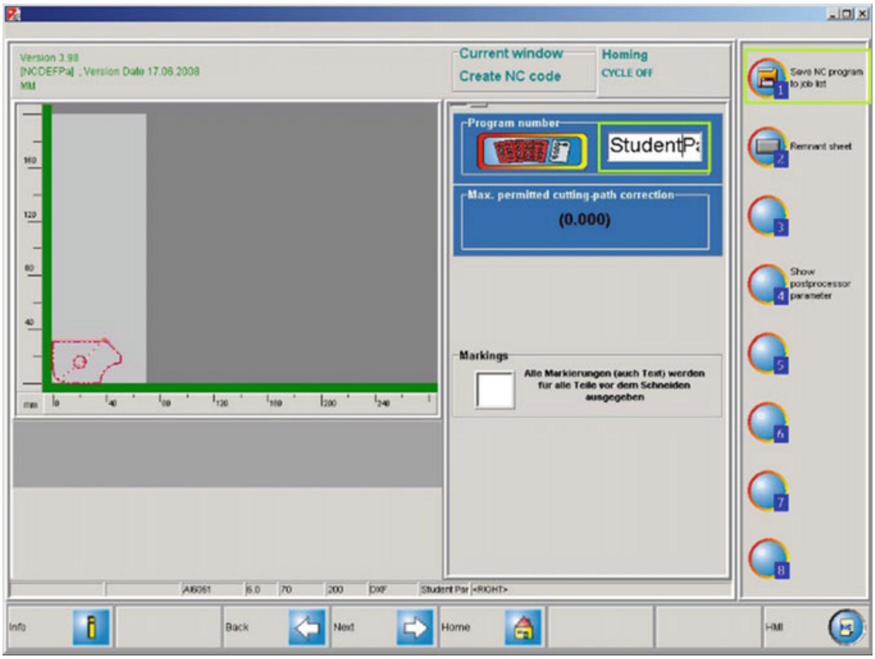


Fig. 25 Save NC program to the job database

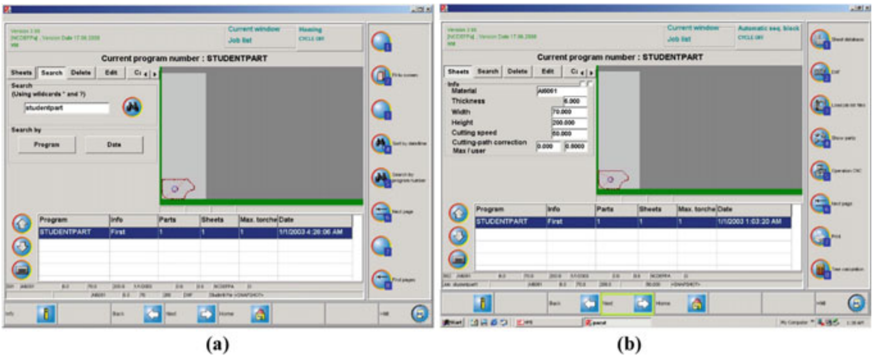


Fig. 26 Loading a NC program from the Job list

comparators, use a light source to illuminate a part placed on a table to obtain a shadow that is projected on a screen. A special optical system (telecentric) is used to obtain accurate measurements of the objects by projecting a shadow with constant size and no warping irrespective of the position on the table.

A Mitutoyo PH-A14 profile projector (Fig. 33) was used as it can measure the linear and circular dimensions of the part, but it also allows highlighting the

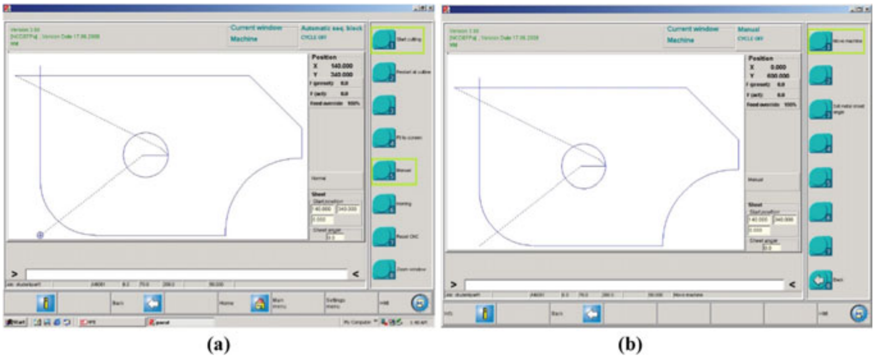


Fig. 27 The cutting head path

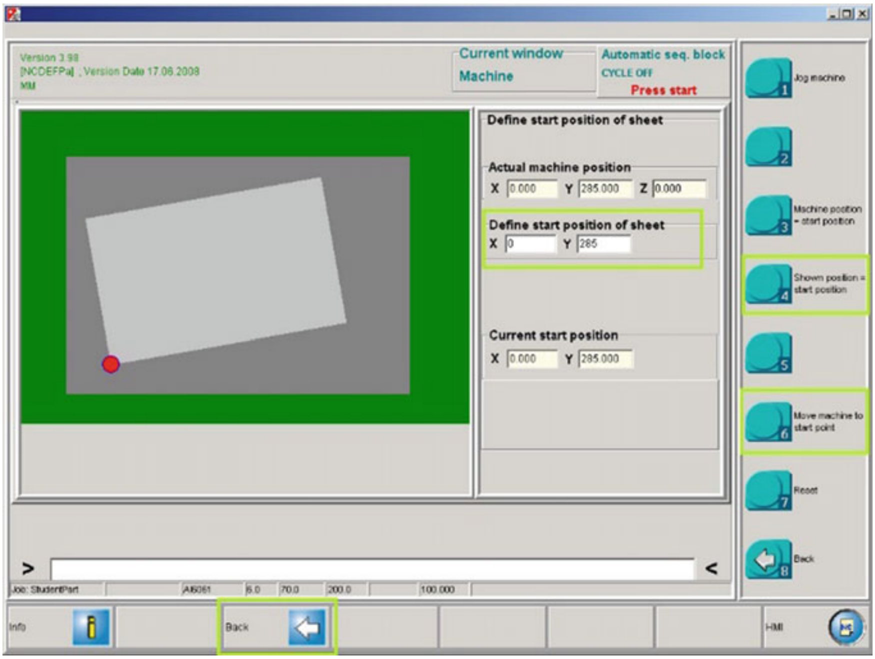
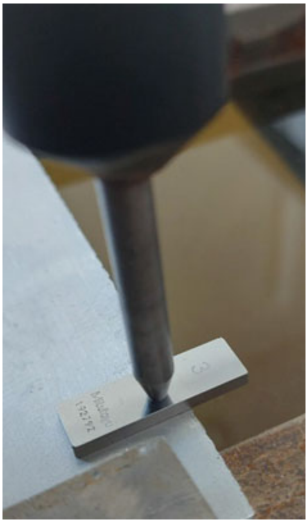


Fig. 28 Setting the origin point

shape defects due to the 10× magnification factor. This is an inverted-reversed projector, meaning that the projected image is flipped both vertically and horizontally compared to the position of the object. It has a digital counter to measure absolute and incremental displacements or coordinates in a range of 200 × 100 mm.

The screen has a rectangular scale printed on it and an additional scaled dial can be mounted for more complex measurements. By aligning the shadow with the scale,

Fig. 29 Setting the standoff distance



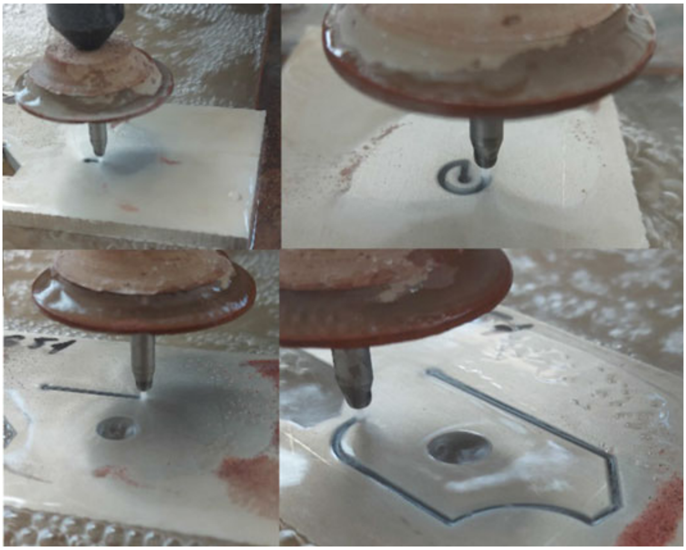


Fig. 30 AWJ cutting progress

the dimensions of the part can be measured from the movement of the table in the cartesian XY coordinates that are displayed on the digital counter. Some dimensions can be determined directly, when the movements are recorded along a single axis, whereas other dimensions require calculations if the movements are on both axes.

The distance between two points in a cartesian XY system, $A(x_A, y_A)$ and $B(x_B, y_B)$, can be calculated using the equation:

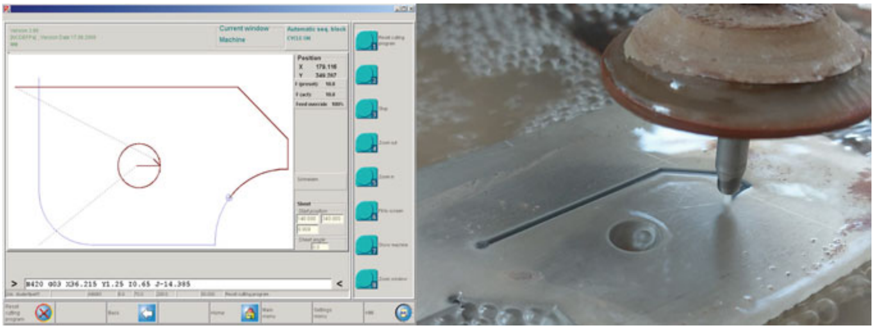
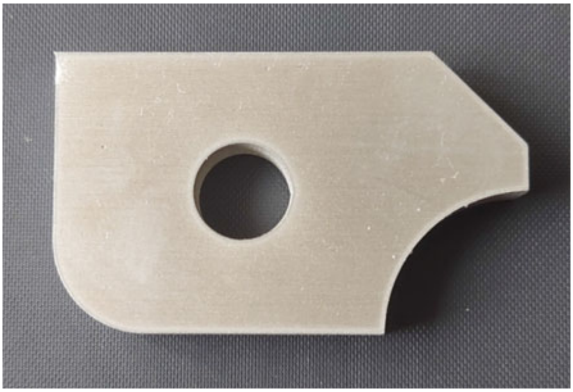


Fig. 31 Monitorization of the cutting head position

Fig. 32 AWJ cut part



$$\Delta_{AB} = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2} \quad (1)$$

6.1 Dimensional Accuracy

The following dimensions were measured: the length of the part L, the width of the part w, the arc radius R_1, shoulder radius R_2, chamfer dimensions l_1 and l_2, and the hole diameter ∅ (Fig. 34). Each measurement was repeated three times and the average value was considered the effective dimension.

For the measurement of the length of part L, the part was aligned with the screen grid and the displacement was recorded on the digital counter. The recorded values and the average length are presented in Table 6. A similar approach was used to measure the width w and chamfer dimensions, l_1 and l_2 (Fig. 35).

For the measurement of arc radius, the contour was first centered (Fig. 36a) and the point was assigned as origin O(0,0). By measuring the coordinates for a series of

Fig. 33 Mitutoyo PH-A14 profile projector

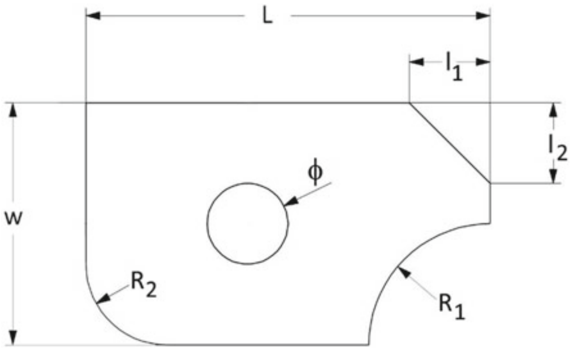


Fig. 34 Part dimensions

Table 6 Linear dimensions measurement

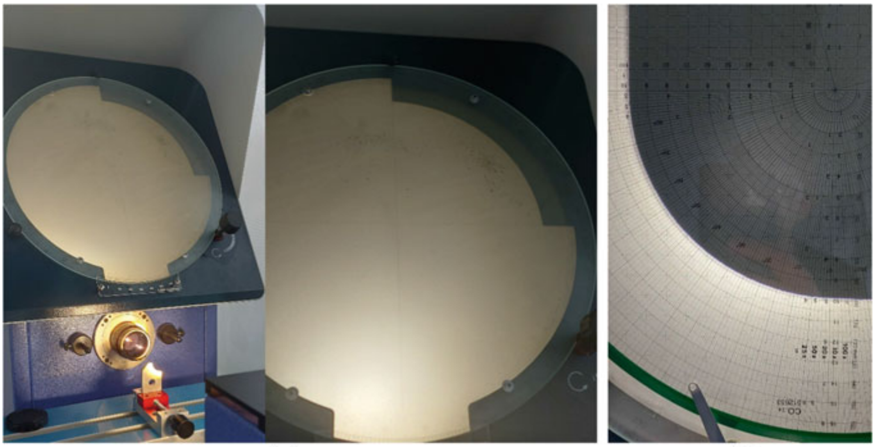
Verified dimension [mm]	Nominal value	Measurement			Average	Error
		1	2	3		
Length L	50	49.95	49.92	49.93	≈ 49.93	0.07
Width w	30	29.91	29.92	29.92	≈ 29.92	0.08
Chamfer l_1	10	9.93	9.95	9.93	≈ 9.94	0.06
Chamfer l_2	10	10.06	9.99	10.07	≈ 10.04	−0.04

Fig. 35 Measurement of part dimensions

points on the circumference, the radii were calculated using the equation mentioned previously and the average value is the arc radius (Table 7).

Shoulder radius was measured using the additional dial for radii and angle measurement (Fig. 36b). The part was first aligned with the axes, then the table was moved until there was the best overlap between the contour and the circular marks of the dial. The radius is calculated as the average value of the displacements and the reading on the dial (Table 8).

For the hole measurement (Fig. 37) three diameters were measured in different directions and the results were averaged (Table 9).



(a) (b)

Fig. 36 Radii measurement

Table 7 Arc radius R_1 measurement

Point coordinates	Radius	Average radius [mm]	Nominal radius [mm]	Error
(14.915, 0)	$\sqrt{(14.915-0)^2+(0-0)^2} =$ 14.915	14.98	15	0.02
(0, 15.075)	$\sqrt{(0-0)^2+(15.075-0)^2} =$ 15.075			
(14.205, 4.59)	$\sqrt{(14.205-0)^2+(4.59-0)^2} =$ 14.92			
(9.86, 11.26)	$\sqrt{(9.86-0)^2+(11.26-0)^2} =$ 14.97			
(4.41, 14.355)	$\sqrt{(4.41-0)^2+(14.355-0)^2} =$ 15.02			

Table 8 Shoulder radius measurement

Verified dimension	Nominal value	Measurement			Average	Error
		1	2	3		
Radius R_2 [mm]	10	9.885	9.865	9.90	≈ 9.88	0.12

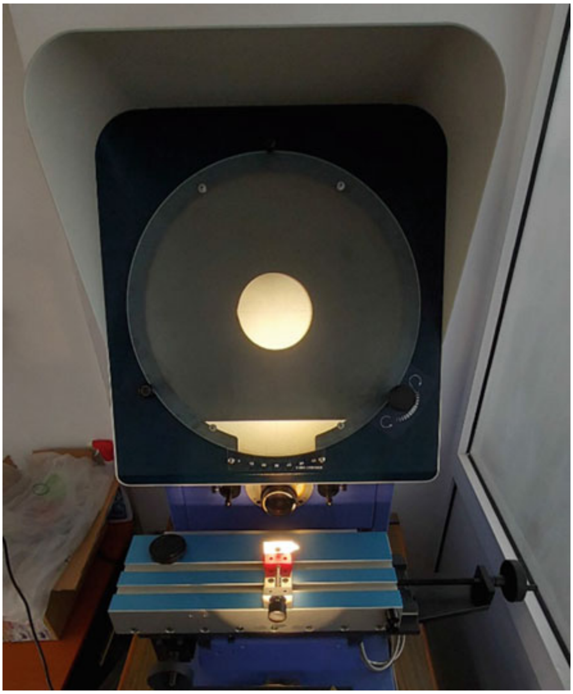


Fig. 37 Hole diameter measurement

Table 9 Hole diameter measurement

Verified dimension	Nominal value	Measurement			Average	Error
		1	2	3		
Hole diameter ∅ [mm]	10	10.16	10.21	10.18	≈ 10.18	− 0.18

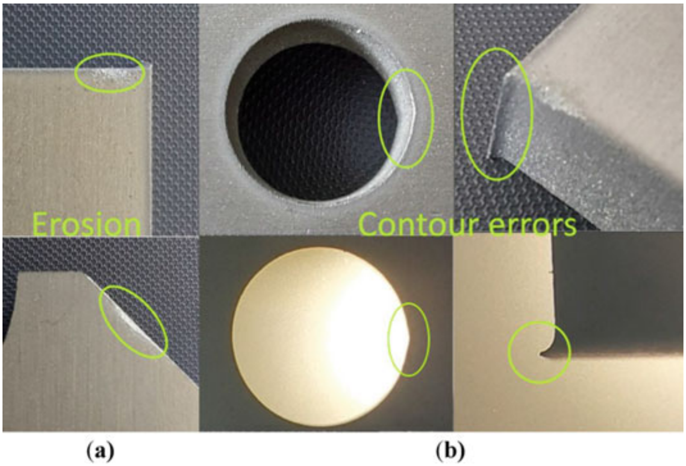


Fig. 38 Defects of AWJ cut parts

6.2 Contour Defects

A series of contour defects can be observed on the part:

- Erosion of the edge produced by the abrasive (Fig. 38a);
- Contour shape errors, such as the roundness deviation of the hole, caused by the prolonged action of the AWJ at the beginning and the end of cutting, or the burr remained at the end of the exterior contour cutting (Fig. 38b).

6.3 Kerf Angle

Kerf angle occurs in AWJ cutting due to the difference between the widths of cut at entrance and exit, respectively. This is caused by the loss of energy of the waterjet and is influenced by various factors, such as the material being processed, the waterjet pressure or the traverse speed. Kerf angle is important when vertical cuts are required. The angle was measured (Fig. 39) and the results are in Table 10.

Fig. 39 Kerf angle

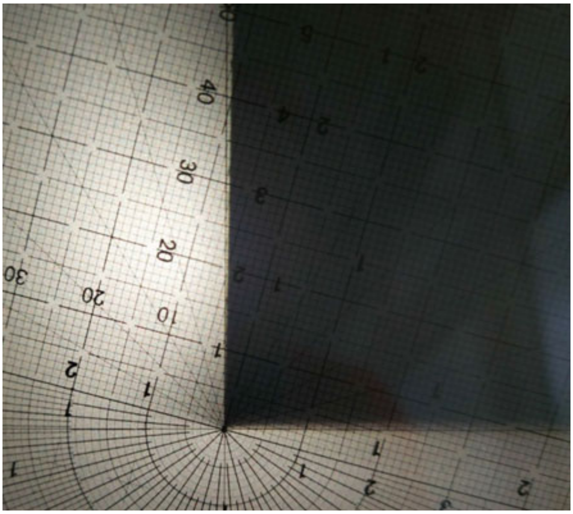


Table 10 Kerf angle

Verified dimension	Nominal value	Measurement			Average	Error
		1	2	3		
Kerf angle α [°]	0	1° 10′	1° 6′	1° 8′	1° 8′	1° 8′

6.4 *Kerf Surface Aspect*

The surface of the cut (kerf surface) is an important element for the quality of the part. Visual examination of the surface reveals the two areas (Fig. 40):

- the fine cut area (1) that has a smoother aspect because the abrasive particles had higher energy and removed the material by abrasion;
- the rough cut area (2) that has more striations because the material is removed by erosion.

Surface rougness Ra was measured in the middle of the kerf surface using a Mitutoyo SJ-201 roughness meter (Fig. 41) and the results are presented in Table 11.

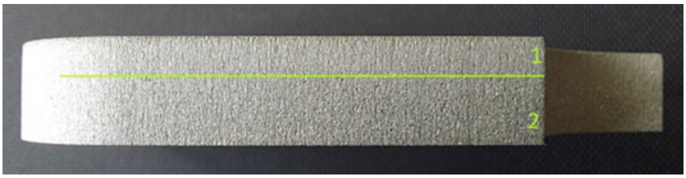


Fig. 40 Kerf surface

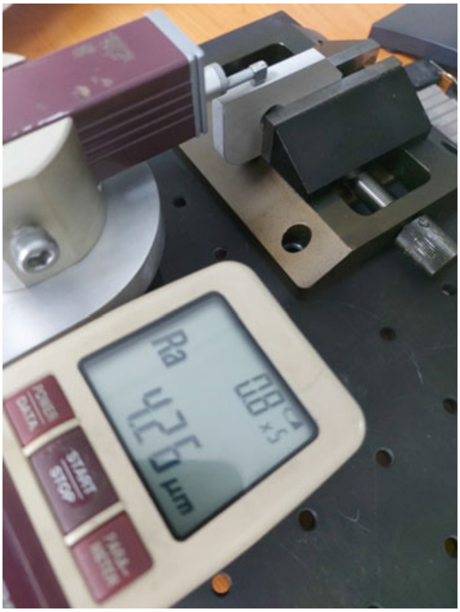


Fig. 41 Surface roughness measurement

Table 11 Surface roughness

Parameter	Measurement					Average
	1	2	3	4	5	
Surface roughness Ra [μm]	4.36	4.38	4.26	4.13	4.27	4.28

7 Deliverables and Assessment

7.1 Quiz—Knowledge Testing

1. Explain the working principle of the hydraulic pressure intensifier.
   ....
   ....
   ....
   ....
   ....
2. Choose the advantage of AWJ cutting:
   (a) It depends on water quality
   (b) There is no heat affected zone on the material
   (c) Reduced levels of noise during operation
3. What is the role of the water filtering subsystem

(a) Reduces the concentration of calcium carbonate
(b) Removes debris from the used water
(c) Increases the pressure of the water jet

4. What is the value of the pressure created by the intensifier?

(a) up to 35 MPa
(b) up to 100 MPa
(c) up to 400 MPa
(d) up to 1000 MPa

5. What is the purpose of the catcher tank?

(a) Movement of the part during processing
(b) Collect the residual water and abrasive particles
(c) Provide water for the AWJ machine

6. What is the speed of the waterjet in AWJ Machining?

(a) 200 m/s
(b) 400 m/s
(c) 900 m/s
(d) 1200 m/s

7. What is the recommended length to diameter ratio for the focalization tube?

(a) 4–20
(b) 20–50
(c) 50–100
(d) 100–150

8. What are the typical values of the interior diameter of the focalization tube?

(a) 0.1–0.3 mm
(b) 0.5–1.3 mm
(c) 0.2–2 mm
(d) 1–2.5 mm

9. What is the standoff value range in AWJ Machining?

(a) 0.1–1 mm
(b) 1–2 mm
(c) 1–5 mm
(d) 2–10 mm

10. Name the disadvantage of the AWJ Machining:

(a) It can only cut simple contour shapes
(b) Precision of the cut reduces when material thickness increases
(c) It is only suitable for soft materials
(d) AWJ increases surface hardening

7.2 Quiz Answers

1. The intensifier is made of two cylinders with diameter ratios from 1/10 to 1/25. On the larger side the pressure on the hydraulic plunger is 5–35 MPa and because of the diameter ratio, in the second cylinder the pressure can rise to 400 MPa.
2. (b) There is no heat affected zone on the material
3. (a) Reduces the concentration of calcium carbonate
4. (c) up to 400 MPa
5. (b) Collect the residual water and abrasive particles
6. (c) 900 m/s
7. (c) 50–100
8. (b) 0.5–1.3 mm
9. (c) 1–5 mm
10. (b) Precision of the cut reduces when material thickness increases

7.3 Measurement Results

Students are required to fill the part drawing with the dimensions obtained after measuring the part by themselves (Fig. 42).

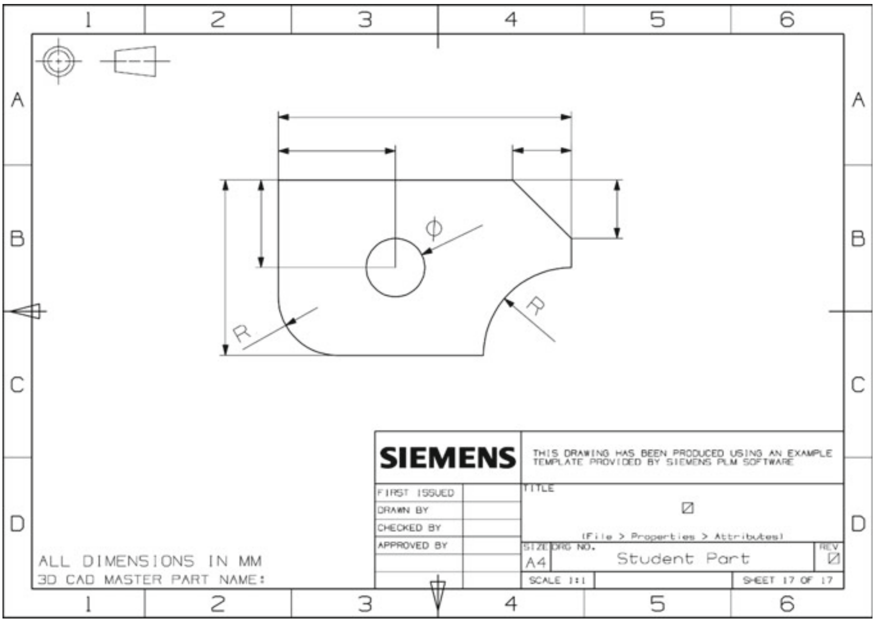


Fig. 42 Measurement report

Observations:

Students are required to mention any observations concerning the aspect and the quality of the part.

....

....

....

....

....

8 Conclusions

This chapter introduces waterjet cutting: the principle of operation, the construction of waterjet cutting machines, the abrasive materials used, kerf geometry and the processing parameters. The purpose of the chapter is to provide students with the basic capabilities for programing and operating the waterjet cutting equipment. A systematic tutorial is provided for creating a specific machining technology, programming the machine, and executing the AWJ cutting operation. A method of controlling the quality of the processed part is also presented. The chapter ends with a knowledge test quiz.

References

Barton.com. (2023). *Technical data and physical characteristics ADIRONDACK HPX garnet abrasives*. https://www.barton.com/wp-content/uploads/2021/04/Technical-Data-ADIRONDACK-HPX.pdf

Engemann, B. K. (1993). *Schneiden mit Laserstrahlung und Wasserstrahl - Anwendung, Erfahrungen.* Verlag GmbH.

Hashish, M. (1987). Method and apparatus for forming a high velocity liquid abrasive jet. US Patent: Vol. 4,648,215.

Hashish, M. (2015). Waterjet machining process. In A. Y. C. Nee (Ed.), *Handbook of manufacturing engineering and technology* (pp. 1651–1686). Springer London.

ISO/TC 44 N 1770: Water jet cutting—Geometrical product specification and quality (2010). https://farsungroup.com/assets/farsun-group-waterjet-iso.pdf

Jegaraj, J. J. R., & Babu, N. R. (2005). A strategy for efficient and quality cutting of materials with abrasive waterjets considering the variation in orifice and focusing nozzle diameter. *International Journal of Machine Tools and Manufacture, 45*(12–13), 1443–1450.

Natarajan, Y., Murugesan, P. K., Mohan, M., & Liyakath Ali Khan, S. A. (2020). Abrasive water jet machining process: A state of art of review. *Journal of Manufacturing Processes*, *49*, 271–322.

Sisodia, V., Gupta, S. K., Salunkhe, S., Murali, A. P., & Kumar, S. (2023). An experimental investigation on machining of hardened AISI 440C stainless steel using abrasive water jet machining process. *Journal of Materials Engineering and Performance.*

Summers, D. A. (2003). Waterjetting technology. In *Waterjetting technology* (1st ed.). CRC Press.