2011 WJTA-IMCA Conference and Expo
September 19-21, 2011 • Houston, Texas

Paper

METHODS FOR AWJ CUTTING PROCESS CONTROL

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ABSTRACT

Is it possible to use optical or IR monitoring to on-line control the AWJ cutting process and which are the benefits? In this paper the results of the experimental work in which it is shown how to use monitoring methods in order to create an AWJ cutting process control. It is pointed out which were the necessary steps which gradually led to control system.

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1. INTRODUCTION

In the manufacturing technologies there is a constant trend towards the closed loop control of manufacturing processes. It is expected that with proper implementation of feedback control several benefits can be achieved: manufacturing process should be more stable with reduced consumption of materials, energy and executed in more optimal processing times.

In AWJ machining workpiece cut with abrasive water jet exhibit a surface texture with characteristic features. Between longer periodic striations several striations with shorter periods can be observed in the Figure 1 (a), which is behaviour typical for complex dynamic systems. Altogether waviness exhibits a rather random character, which limits its use for accurate machining operations, where tolerances less then 1/20 mm are required. Possible solution is in the implementation of the control system with response fast enough to compensate for the variations of dynamic parameters.

In this paper it is reported on the implementation of AWJ cutting process online control based on optical monitoring of AWJ cutting of transparent material and on the monitoring of the AWJ cutting front propagation in opaque material by IR (infra red) thermography.

Online process monitoring is a first step towards process control, therefore several experimental principles were tested relatively soon after AWJ cutting invention. Hashish (1988) performed AWJ cutting process visualisation on transparent material, polymethyl-methacrylate (PMMA), by means of a high speed camera. The experiment clarified to some extent the mechanism of cutting front propagation and proved the existence of a step formation on cutting front. It was suggested that photo-elastic study and infrared visualization should be performed. Photo-elastic study was performed on transparent birefringent material by Ramulu (1993), who identified two distinctive processes: micro-cracking due to pure waterjet and micro-crack nucleation and micromachining due to abrasive action. AWJ machining thermal distribution on workpiece was first measured by Ohadi et al. (1992), who inserted a matrix of thermocouples in the lateral workpiece surface and bottom surface regarding to the traverse direction of the cutting head movement. It was shown that temperature peaks rose up to 70ºC and found out that caution should be paid when generalizing AWJ as a cold process. Among the other principles used for monitoring we would like to highlight the water backflow force sensor. Signal from back-flow pressure sensor is induced by the jet detection on the cutting front and can be used to monitor the AWJ cutting process. The pressure sensor was mounted on the cutting head in the position opposite to the traverse direction of the AWJ cutting head as is shown in the Figure 1 (a). Attributes of acquired electric signals were after processing easily classified in three quality groups with high level of significance, Lebar et al. (2003).

The feasibility of monitoring of the AWJ cutting process and the mixing tube wear, by IR thermography was first studied by Kovacevic et al. (1996). Their results are in good agreement with results obtained independent and by means of different method by Ohadi et al. (1992). They performed also the monitoring of the AWJ cutting head, especially mixing tube wear. It was reported that IR thermography is suitable for visualization of cutting mechanisms in opaque materials, but they concluded that the change in traverse speed yields only marginal effect on the temperature distribution in the workpiece.

We were challenged by these results to find the range of AWJ machining parameters at which different AWJ cutting head speeds would result in significantly different IR thermogram. Our preliminary experiments of AWJ cutting monitoring showed that the curvature of the cutting front resembles the striation marks on the machined workpiece well; Lebar, Junkar (2001).

Three years ago in our group a comprehensive study of striation formation mechanism was conducted by Orbanic and Junkar, (2008). During this research a high speed CCD camera was used to observe and measure the striations in transparent material. Acquired image sequences were processed off-line in order to determine the characteristic frequency of step formation. It was logical to continue this work towards online monitoring and full control of the AWJ cutting process.

2. EXPERIMENTAL WORK

In the first phase of experimental work concerned with this paper an AWJ cutting process was observed with statically positioned IR camera. Measurements were processed offline and compared with surface textures, measured by macro photography. In the second phase a full control loop was implemented by using optical monitoring of transparent workpieces.

2.1 Thermographic monitoring

Experiments with IR monitoring of AWJ cutting were carried out on 2-axis AWJ cutting system OMAX 2652A, equipped by high pressure pump BHDT Ecotron 403 (Austria). IR camera used during experiments was FLIR ThermaCam S65 with thermogram image size of 320 x 240 pixels, thermal sensitivity 0.050 K at 30°C, 14 bit resolution and capture rate of 25 frames per second. Thermograms were stored in data format suitable for further processing by Matlab software. Schematic overview of the experimental setup is in the Figure 2.

IR monitoring experiments were performed on 25.4 mm thick and 46 mm wide workpieces made of aluminium alloy 6061-T6. Particular material was selected to be in correspondence with literature and since this material is one of the most frequently machined materials by AWJ. The face of the workpiece, which was turned towards the IR camera, was coated with black enamel paint of known emissivity $\varepsilon = 0.80$. Traverse direction of the cutting head was parallel to the workpiece face exposed to IR monitoring as is shown in Figure 2. The distance of the cut from the black enamel coated surface of the workpiece was set to 1 mm.

The IR thermograms acquired during experiments described in this paper were acquired to a sequence of images with frame rate of 25 frames per second. Five selected frames out of complete sequence are shown in the Figure 3.

IR camera captured wider scene than just workpiece as can be seen in the Figure 3 therefore a location of AWJ cutting head had to be determined for each frame by discrete correlation of thermogram and a part of thermogram representing the cutting head which was taken and memorized a priori. The element of correlation matrix with maximal value corresponds to the location of the cutting head. The area occupied by the workpiece in the thermogram was determined manually by point-and-click interaction with the image on the computer screen.

Coordinates of the clicks determined the image sub-matrix which corresponds to the workpiece. Since workpiece and camera remained fixed during the experiment it was necessary to manually determine workpiece position only on single frame. Example of workpiece thermogram, extracted from the wider scene can be observed in Figure 4. Thermogram exhibits a cutting front shape typical for waterjet process. In order to numerically describe the cutting front shape a computer program searched through the lines of thermogram and identified the coordinate of the hottest spot in the particular line.

A polynomial of the second order was fitted with constraints to the set of hot spot coordinates, using function Matlab mmpolyfit written by Hanselman and Littlefield (2005). The fitting was constraint with demand that the slope of the cutting front is parallel to the waterjet direction at the top surface of the workpiece, therefore the second coefficient of the polynomial is always zero and the constant term equals to location of the abrasive waterjet cutting head. In the Figure 4 region of interest (ROI) in the thermogram with fitted line corresponding to cutting front can be observed.

Procedure was repeated automatically on every acquired frame in the series of thermograms, which were acquired with frequency of 25 frames per second. Coefficients were stored for further correlation with surface texture characteristics.

2.2 Surface texture measurements

Surface texture characteristics of machined workpieces were evaluated by digital processing of images acquired by a universal Keyence (Japan) machine vision system consisting of a MegaPixel CCD camera CV-025 with 1628 x 1236 pixels and a system controller CV-2600. To emphasize texture marks suitable lightning conditions were chosen, i.e. the light incident angle was set to 15^{o} as is shown in the Figure 6. Acquired images were subsequently processed by our SEMAC software Lebar et al. (2001), written in Matlab.

Surface texture analysis is the first part in the workflow of the presented research work. It is inherently an off-line method which derived a relation between surface texture parameters and surface roughness, thus promoting the surface texture parameter as the reference parameter of the AWJ control system.

As it is often quoted “the surface texture of a finished geometrically defined body is the fingerprint of all process stages of the manufacturing process”, Trumpold (2001), therefore its importance is straightforward. Starting with an evaluation of AWJ machined surfaces a methodology was developed which showed that parameter of the striation lines is closely related with surface quality and that it can be used in the procedure of the cutting process optimisation, Lebar et al. (2001).

2.3 Optical monitoring

Optical monitoring of AWJ cutting was performed on polymethyl-methacrylate (PMMA) strips with rectangular cross section, 27 mm wide and 8 mm thick. Stripes were 260 mm long. Appropriate illumination of the emerging cutting front was achieved by use of three bright red light emitting diodes from right side. PMMA strips acted like a light guide, delivering the light to the cutting front.

It was observed, that light propagated with rather low attenuation through the PMMA strip and scattered mostly on the cutting front, thus giving very good contrast between the material-jet interface zone and undisturbed material. Cutting front was monitored by USB camera Philips SPC 1000NC with 2.0 MP CMOS sensor, 16 bit colour resolution and maximal frame rate 90 frames per second. Image acquisition was implemented in MATLAB software environment. Camera was placed in a water resistant box and attached to the cutting head, thus it was at constant distance from the cutting front during the experiment as it is shown in the Figure 5.

3. AWJ PROCESS CONTROL

Experimental setup described in previous section was implemented into the AWJ process control loop by using several methods, mostly from the image processing domain. In the Figure 8, the relations between the elements of experimental setup and evaluation methods which enabled the functionality of the system can be observed. It has been shown in the preceding sections, how to monitor the AWJ cutting process online by means of IR thermography and visual monitoring. AWJ process reference parameter was identified and its correspondence with cutting results validated by comparison of workpiece macro-photography and digital image processing in Lebar et al. (2010). In the next step which is to be described in this section, a step towards AWJ cutting process control was made.

3.1 Control System

Communication between CNC controller of AWJ machine, high pressure valve, abrasive inlet switch and image acquisition camera was supervised by a PC running a script in Matlab. In order to significantly reduce the information flow from PC towards CNC controller and to decrease PC processor load a programmable logic controller (PLC) shown in the Figure 7 was inserted between PC and AWJ machine. Matlab relieved of controlling the CNC trivial tasks can thus successfully tackle the process identification and process control.

At the present phase of our work with AWJ cutting process control, experiments were performed on transparent material and thus instead of IR camera a digital video camera has been used as described in the section 2.3 Optical monitoring. Computer programme continuously acquired images of the cutting front and evaluated the parameter of fitted second order polynomial with constraints. If the parameter is smaller than some reference value, PC based computer programme sends a command to interface controller in order to reduce the AWJ cutting head traverse rate or to speed up in the case that parameter is larger than reference value.

The control strategy used in this experiment was to increase the cutting head traverse speed as much as possible, but to keep the performance index close to the reference value. Strategy is realised by cutting head traverse rate increase or decrease in predefined sequence of traverse rate steps. The predefined sequence steps are becoming larger as difference between current performance index value and reference performance index value increases as is illustrated in the Figure 9. Regarding this characteristics of control strategy it can be termed sequential-proportional type of control strategy.

3.2 Process control results

The results of the control strategy can be observed in the Figure 10. In the graph (a) is the relation of traverse rate vs. time and in the graph (b) is the value of process parameter ***a*** vs. time. In the graph (c) it is shown the geometrical implication of parameter ***a*** variation. The reference value of performance index was set to -1.0*10-3 and it can be observed, that control strategy successfully controlled the traverse velocity in such a way that parameter ***a*** varied in the range +/-0.25*10-3.

4. CONCLUSION

Based on experiments of AWJ cutting process monitoring by IR thermography a full control loop of AWJ cutting has been performed and results reported in this paper. It has been shown, that curvature of the cutting front can be used as a parameter of the process and can be determined from the thermo-graphic images in the case of cutting opaque materials or from the optical images in the case of transparent materials. It can be anticipated that applicability of the proposed system (Cvjeticanin, Lebar et. al., 2011) is mainly in the research domain where it can shorten tedious experimentation procedures with several new materials.

Regarding results obtained by experimental setup presented in Figure 2 and Figure 5 it was shown that leading coefficient of second order polynomial (coefficient ***a***) fitted to the cutting front correspond to the resulting workpiece texture well and can be thus used as a process control parameter.

5. ACKNOWLEDGMENTS

This work is partially supported from the Slovenian Ministry of Higher Education, Science and Technology with the programme Innovative production systems (P2-0248), MANUNET project “AWJ manufacturing technology for composite parts for aeronautics & nautics” in which the Laboratory of Alternative Technologies from the University of Ljubljana and Fatronik-Tecnalia are collaborating (3211-09-000549).

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7. GRAPHICS

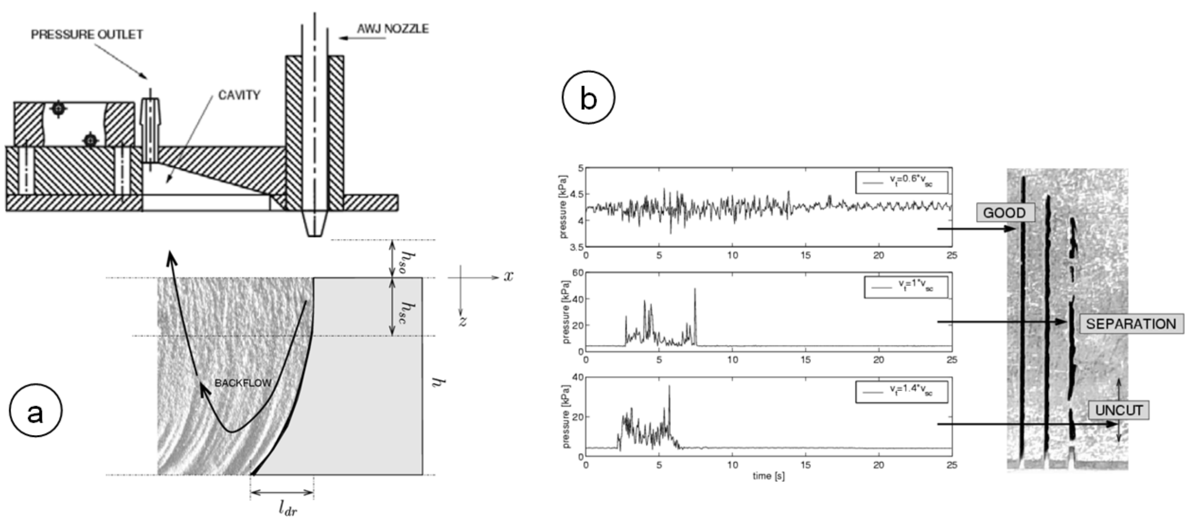

Figure 1. One of possible AWJ cutting monitoring solutions. Generation of the water backflow and position of the sensing screen is schematically shown on left (a). Acquired pressure signals on the workpiece of thickness h=30 mm. The separation cut speed for this workpiece was v_{sc}=1.0 mm/s (b); Lebar et al. (2003).

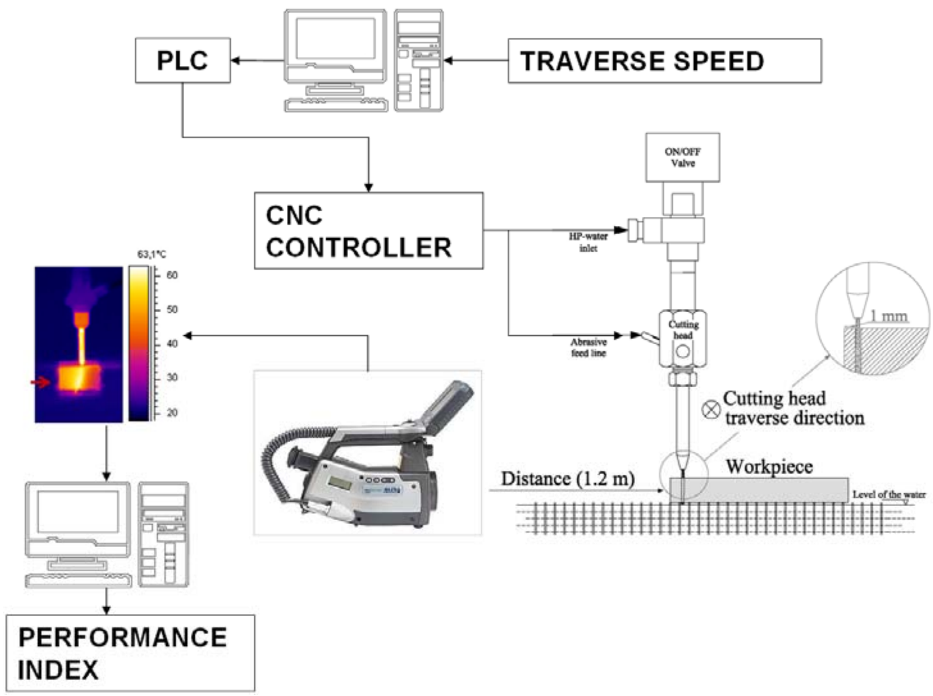

Figure 2. Schematic overview of the experimental set-up.

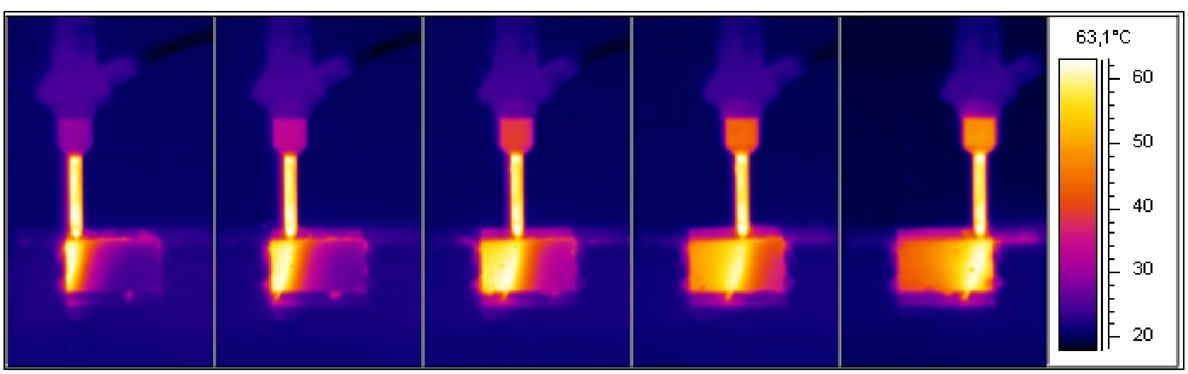

Figure 3. Selected frames from the recorded sequence of IR thermograms during AWJ cutting.

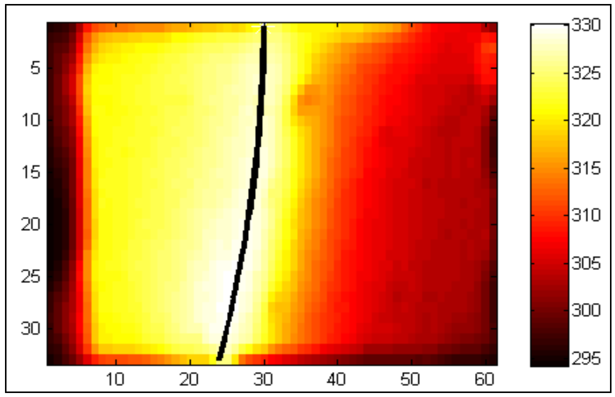

Figure 4. Region of interest (ROI) in the thermogram acquired during AWJ cutting with fitted line corresponding to cutting front.

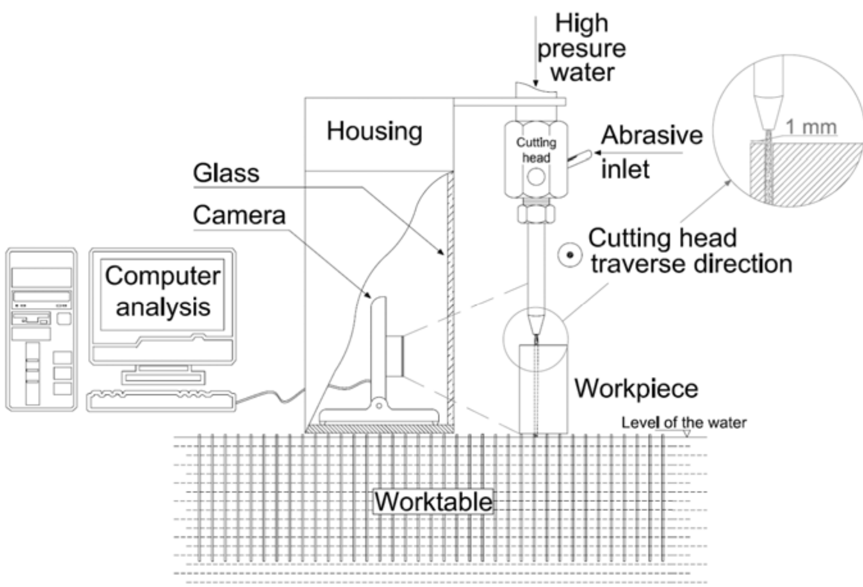

Figure 5. CCD camera attached to the AWJ cutting head.

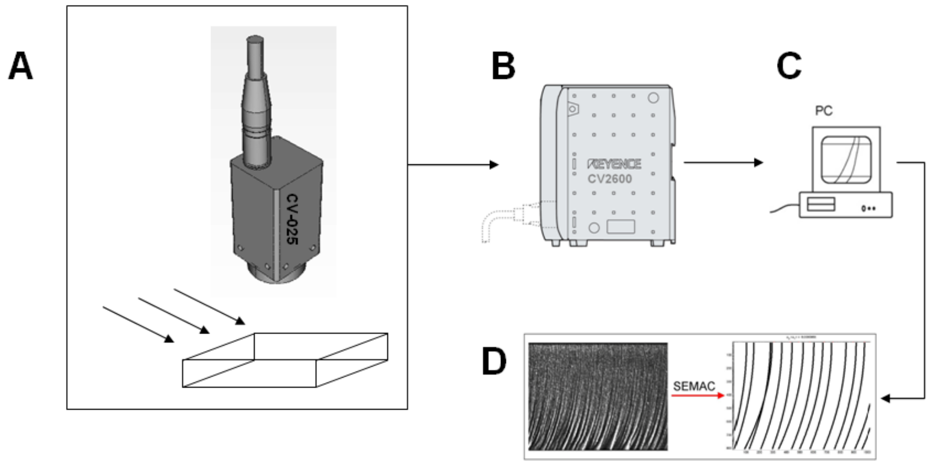

Figure 6. Surface macro photography setup on left side (A) and extracted striation marks after processing with SEMAC software (D); Lebar, Junkar, (2001).

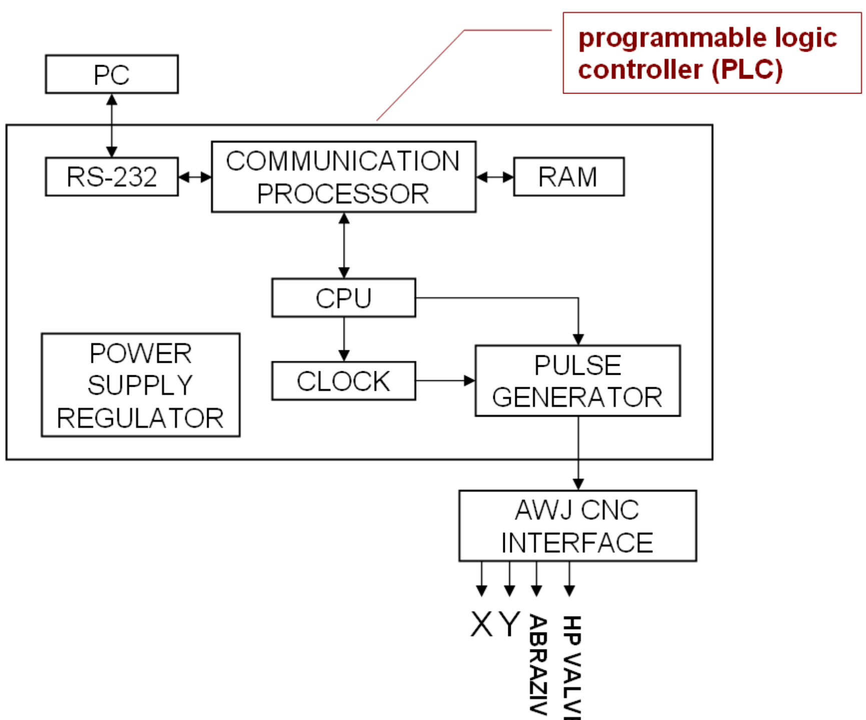

Figure 7. Interface between PC and AWJ cutting machine was realised by PLC based interface.

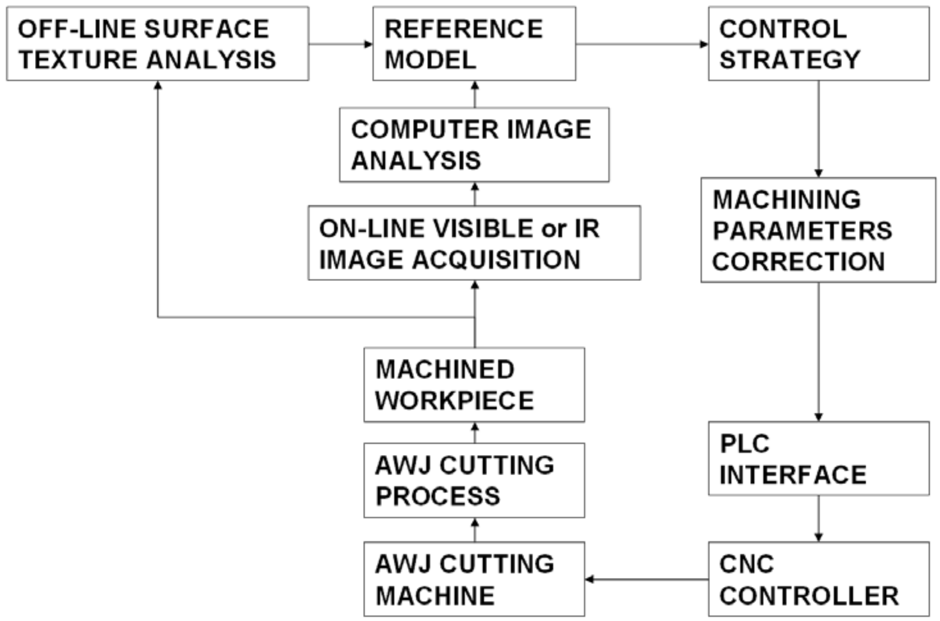

Figure 8. Simplified scheme of AWJ cutting process control system.

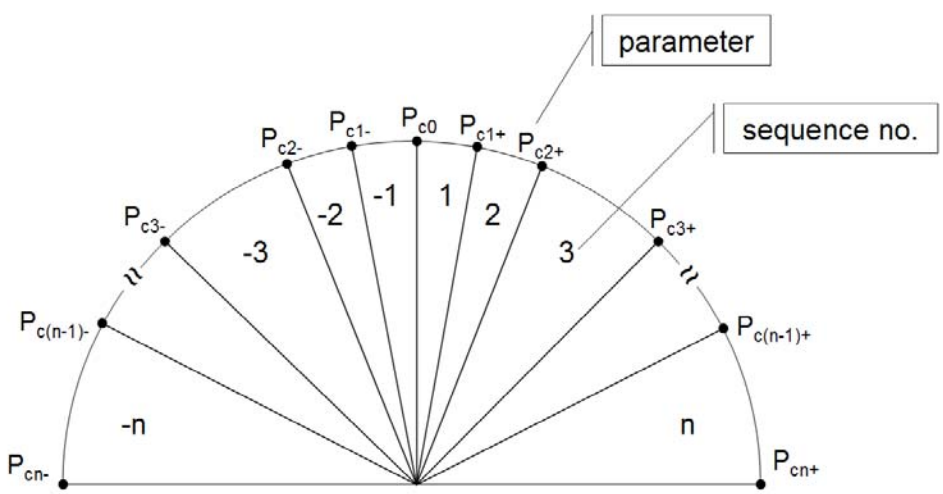

Figure 9. Sequence of process parameter P grows proportionally larger as distance from reference value P_{c0} increases.

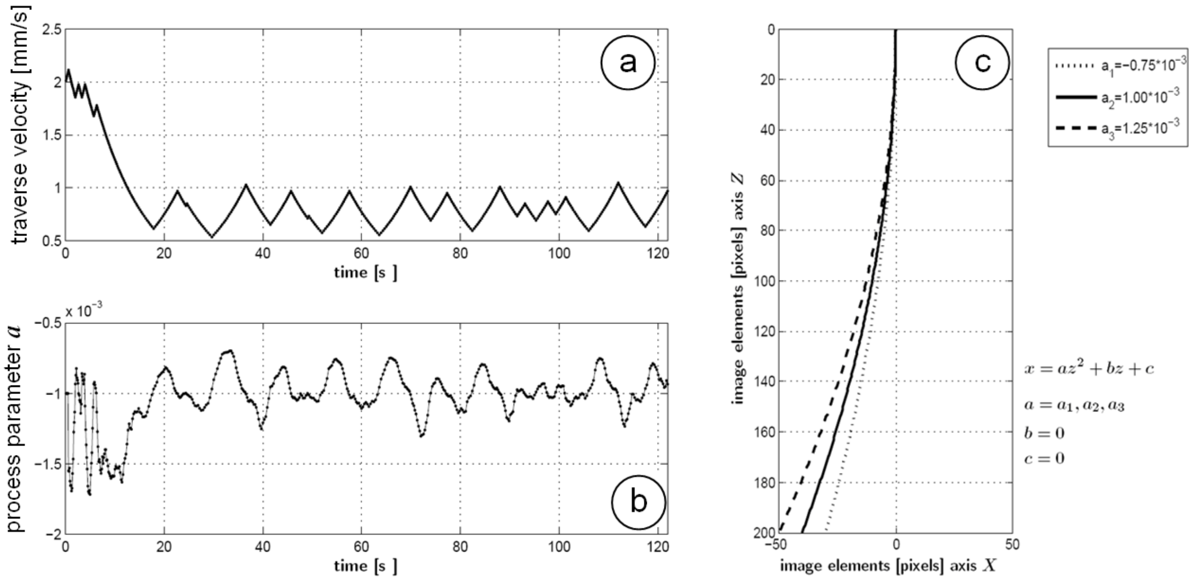

Figure 10. Traverse rate of AWJ cutting head (a), corresponding process parameter – cutting front curvature ***a*** (b) and (bottom plot) vs. time.

8. NOMENCLATURE

a, b, c	parameters of function fitted to the cutting front
t	time [s]
h	thickness of material [mm]