The reproducibility in AWJ cutting: an experimental case

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ABSTRACT

Abrasive waterjet (AWJ) cutting is one of the most rapidly improving technological methods of cutting materials. In order to improve the accuracy of AWJ machining the effect of the process parameters and the external factors has to be known. This paper concentrates on the reproducibility of an experiment where the effect of hardness of the workpiece on the cutting quality was studied. In particular, it was shown that the effect of the hardness on the surface finishing is connected with material removal mechanism: in the cutting wear zone the hardness acts favorably on the roughness surface of the workpiece while, in the deformation wear zone when the hardness of the workpiece increases, the roughness of the kerf is worsened. In this paper, in order to achieve the same result, different experimental research was carried out varying the process parameters. In particular, it was demonstrated that the most important process parameter is the jet power; since jet power depends also on the state of consumable components, its control is nontrivial.

1 INTRODUCTION

Cutting with abrasive water jet (AWJ) is a non-conventional machining process which uses high speed water jet for accelerating very hard grains and thus enabling the removal of workpiece material. Almost every kind of material regardless of their composition, structure, hardness or other physical-chemical properties can be successfully machined. Moreover, the process is cold and there is absence of heat affected zone. However, in comparison to other non-conventional processes such as laser or WEDM (Wire Electrical Discharge Machining), AWJ can result in a not completely satisfying accuracy and quality of the cut if not properly controlled (1).

Many parameters affect the cutting quality. These parameters can be subdivided in two groups: the first one includes the process parameters such as water pressure, abrasive flow rate, type and mesh of abrasive, traverse rate and geometrical characteristics of components of the cutting head. The second one is related to external factors such as pressure fluctuation, abrasive flow rate fluctuation, vibration of the cutting head and of the workpiece, wear of components of the cutting head.

The nozzle and focuser tube are critical components because they directly influence the precision, performance and economics of the AWJ process (2). Wear of the mixing tube results in degradation of the waterjet coherency and kinetic energy. Improvements in nozzle and mixing tube wear characteristics are therefore believed to be critical for the continued growth of the technology. Literature reports several works about this topic.

In (3) the authors are concentrated on the measurement of the wear profiles to understand the wear mechanisms that are active in the process. In (4) an accelerated wear test method was proposed to provide a good indicator of nozzle performance under long-term service conditions. Experimental studies carried out to investigate the influence of orifice and focusing tube bore variation on the performance of abrasive waterjets in cutting aluminum alloy are reported in (5). The wear of orifice and focusing tube was assumed uniform. The results showed that orifice size is one of the major contributing parameters for the depth of cut while for the kerf width, the focusing tube size is the major factor. Moreover the surface roughness is greatly influenced by the focusing tube size.

The AWJ kerf can be characterized in term of both efficiency of the process and qualitative aspects. The efficiency can be valuated considering the maximum kerf depth; as regards the quality, the most important indexes used are the surface finish and the conicity of the kerf. The surface of the cut is in fact characterized by the striation formation curved in the opposite direction of the cutting head and the cut is tapered.

In literature experimental and analytical research efforts have been carried out to get previsional models for maximum kerf depth and for the surface finish in AWJ cutting.

The topography of AWJ generated surfaces has been studied by some researchers. Based on a flow visualization study of the waterjet cutting process, Hashish proposed that a waterjet cut surface consists of two cutting regions (6,7). The first region (the top cut of the surface) is dominated by the cutting wear mode where penetration occurs in a small impact angle. The second region (the bottom part of the surface) is dominated by the deformation wear mode where penetration occurs in a large impact angle. The surface is smooth in the first region but is marked by striations in the second region.

The roughness parameter is strongly related to depth of cut and cutting speed for the striation zone. Its value increases rapidly as depth of cut or cutting speed increases (8). In (9) a model for predicting the depth of cut of abrasive waterjet in different metals was presented. Materials were characterized by two properties: the dynamic flow stress (i.e. evaluated by dynamic tests) and the critical velocity. The dynamic flow stress used in the erosion model was found to correlate with a typical modulus of elasticity for metals.

In (10) the effect of heat treatment and abrasive type on depth of cut was investigated. The research shown that in cases where the workpiece hardness is much less than that of the abrasive material, hardness alteration by heat treatment may become insignificant on the depth of cut but has effect on the length of the cutting wear zone. As regards cutting obtained at high traverse rates, only deformation wear occurs and may correlate with fracture strength. A threshold hardness ratio, between the material and abrasives, needs to be exceeded for efficient material removal. Once this threshold is exceeded, the material removal may belong to either cutting wear or deformation wear

The effect of heat treatment on erosion resistance was found insignificant in (11): the relative change in abrasive particle and target material hardness is very small. A slightly different result was found in (12), where the effect of the hardness of the workpiece on the surface of the kerfs was studied. The results showed that the effect of the hardness on the surface finish is connected with material removal mechanism: in the cutting wear zone the hardness acts favorably on the roughness surface of the workpiece while, in the deformation wear zone when the hardness of the workpiece increases, the roughness of the kerf is worsened.

Aim of the present work is to assess which process parameters have to be controlled to fully reproduce the results of the previous experiment (12).

2 THE REFERENCE CASE

2.1 Experimental setup

The experimental setup and results already reported in (12) are used here as a reference for further investigation. Let us summarize the details of this reference case, dividing the information into three main groups: equipment data, specimen data and process parameters.

Equipment:
- diameter of nozzle: 0.3 mm
- length of focus: 76 mm
- diameter of focus: 0.8 mm
- condition of nozzle and focuser: partially worn

Specimen:
- geometry: bars 10 mm thick
- material: carbon steel (C40 UNI EN 10084)
- metallurgical state: both normalized (as is) and water quenched to about HV 520

Process parameters:
- standoff distance: 2 mm
- traverse rates: 100, 120, 140, 160, 180, 200, 220 and 230 mm/min
- water pressure: 300 MPa
- abrasive: GMA Garnet, mesh 80
- abrasive flow rate: 6 g/s

Traverse rate of 230 mm/min was found to be the limit traverse rate that permits completely separation of the kerf.

2.2 Result analysis

Roughness data, measured at different depths (1, 5, 9 mm distance from the entry side), were collected. For roughness measurement, a portable surface measuring system

(Diavite DH-5) was used. Exploration length of 15 mm and cut-off length of 2.5 mm were selected.

Each roughness measurement was evaluated by averaging four values, taking into account two factors:

- probe travel direction (either same or opposite to the cutting head);
- side of the kerf.

All tests were repeated twice, therefore each value is obtained from eight different measurements, although not independent from each other.

Basing on such data, the following Figure 1 could be produced. In this figure, black marks (identified by "N") refer to normalized specimens (the subsequent number indicates the measurement depth), while white marks ("WQ") refer to hardened ones.

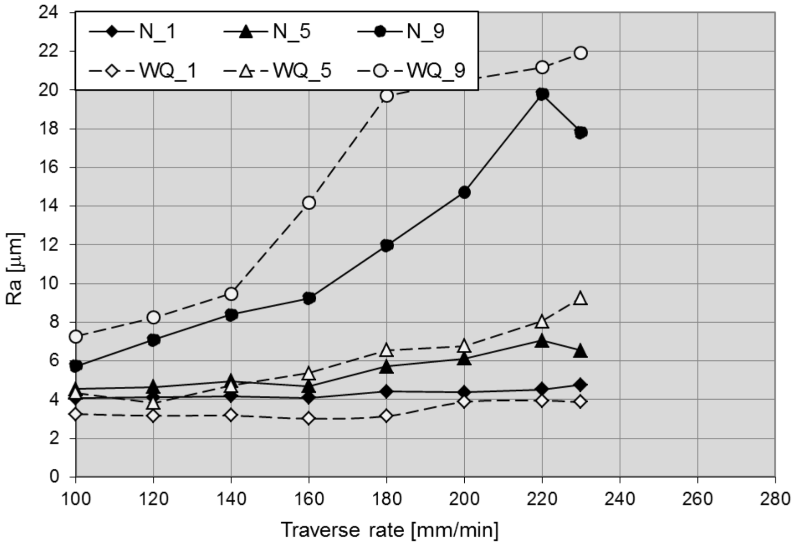

Figure 1 – Results from the reference campaign, as reported in (12)

A peculiar behavior could be observed in Figure 1. Close to the entry side, hardened specimen showed lower roughness, while about the exit side this effect is reversed. This behavior can be connected to jet power that, decreasing with depth, is likely to activate different removal mechanisms. This remark is compatible with the data taken at intermediate depth (5 mm, N_5 and WQ_5): at low traverse rates, when more energy is transferred, hardened specimens show better roughness as it happens at low depth.

This reference case is assumed to be well reproduced when the above mentioned effect can be seen. Absolute values of roughness will be considered as well.

Information about jet power were collected indirectly. First, limit passing traverse rate was evaluated by visual observation at the start of the test and (as said) it was found to be equal to 230 mm/min. Second, another indirect assessment of jet power was performed by estimating the jet exit angle, as suggested in (13, 14). Photographs of the kerf side were taken through an optical microscope and lines, tangent to the striations were drawn as shown in Figure 2.

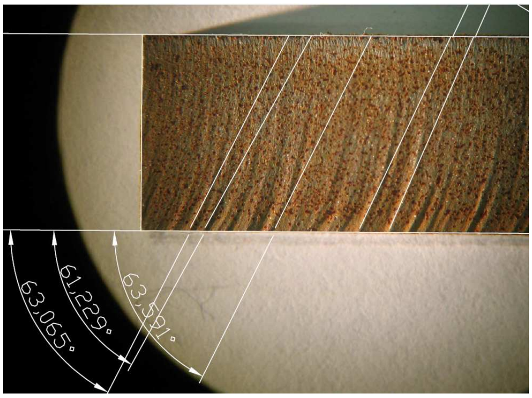

Figure 2 – Exit angle evaluation

For each experimental condition (treatment), two specimens were selected, cut with a fixed traverse rate of 200 mm/min. Both sides of the kerf were studied, thus yielding a total of 4 pictures per treatment; 20 measurements were taken for each treatment. The jet exit angle was computed by averaging the measurements.

3 REPRODUCTIONS OF THE EXPERIMENT

3.1 First reproduction: case A

At first, a new experimental campaign was carried out to repeat the reference experiment. All experimental details had been kept constant, in particular the water pressure was 300 MPa. The AWJ system was the same as for the reference case; anyway, nozzle and focuser tube had to be replaced for this campaign. Thus, the condition of nozzle and focuser changed from “partially worn” to “new”. In this case, it is reasonable to assume that the erosive power of the jet was significantly increased. This assumption was tested through the evaluation of jet exit angles, when lower exit angles were estimated (see Figure 4). Accordingly, passing cut was possible at the higher traverse rate of 280 mm/min.

Roughness data were evaluated by averaging several measurements as it was done for the reference case; in this reproduction, anyway, four repetitions were carried out. The results, shown in Figure 3, do not display the same behavior as reported for the reference case. The hardened specimens showed higher roughness values than the corresponding normalized ones. Also in this case the difference in roughness between the two set of samples (N and WQ) are bigger at higher traverse rates, showing a weak effect of jet energy; in any case, a clear reproduction of the standard case was not achieved.

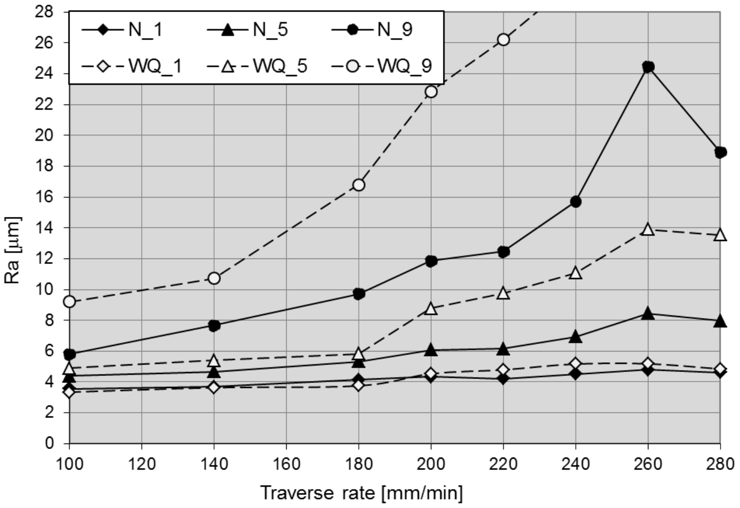

Figure 3 – Results from reproduction case A (water pressure 300 MPa)

3.2 Second reproduction: case B

In this case the experiment was designed to reproduce the same jet power as in the reference case. This goal was reached by varying the water pressure and by selecting a suitable value though a trial and error procedure; water pressure of 250 MPa was found to match this requirement. Passing traverse rate was equal to 240 mm/min in this case. Average exit angles, compared with the previous cases, are reported in Figure 4.

Repetition of the experiment was carried out using the same protocol previously reported; also in this case, four repetitions were executed.

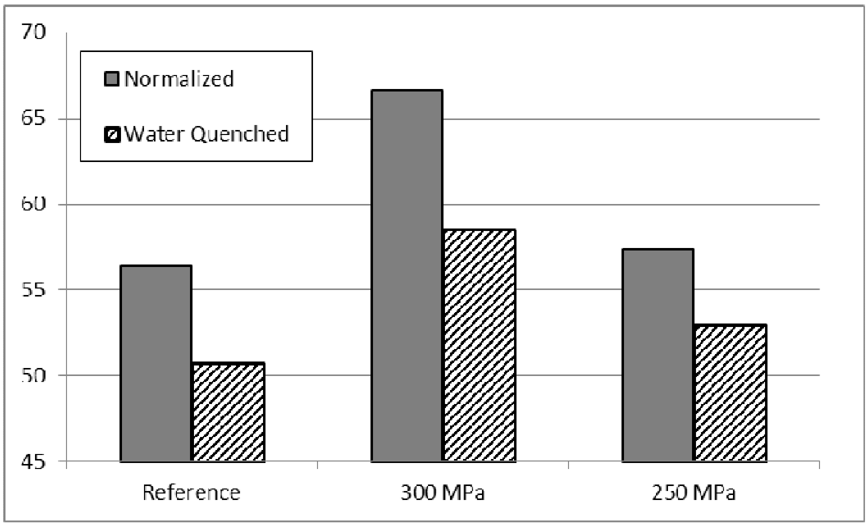

Figure 4 – Chart of exit angles

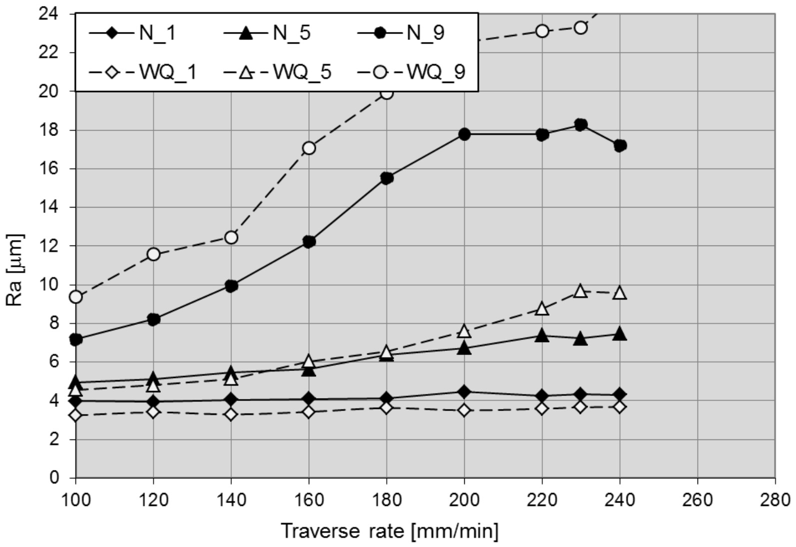

Figure 5 – Results from reproduction case B (water pressure 250 MPa)

In this case, the comparison of roughness on the two sets of specimens shows the general trend outlined for the reference case: lower roughness for hardened samples at shallow depth and the very opposite at depth 9 mm. Also the behavior at depth equal to 5 mm is similar to the reference case, showing a transition at varying traverse rate.
Concerning the absolute values of roughness, the results of case B proved to be able to match the reference values very well.

3.3 Another significant factor

Figure 6 reports the results of a cutting test carried out without using fixturing devices. In this case, the workpiece was just laid on the cutting table and held in position using weights; all other experimental conditions were the same as in case B. Only one WQ specimen, containing two series of cuts, was tested. For comparison, results for experiment B are reported in Figure 6.
Because of the peculiar (and undesired) behavior of the roughness data, all results shown in Figure 6 were discarded; all other data in the present paper are produced by using fixtures based on a screw clamp. The peculiar behavior shown in Figure 6 may be due to vibration effects. In particular:

- the roughness peak at 180 mm/min may be due to resonance phenomena;
- roughness data showed to be correlated with traverse rate rather than the geometrical location in the specimen;
- this problem was never recorded using screw fixtures.

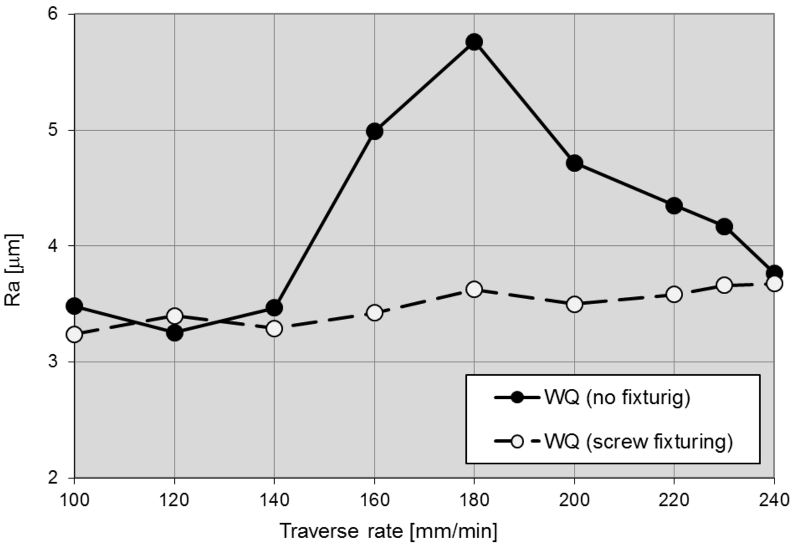

Figure 6 – Possible effect of fixturing on roughness; results at depth of measurement 1 mm

The trend shown above may be a further confirmation of the importance of a correct fixturing. It is worth noting that no other signal (i.e.: special noise, evident abnormal mechanical vibration etc.) could suggest the occurrence of a new phenomenon. Under constant process parameters (just one traverse rate) detection of malfunctioning may be really difficult and abnormally high roughness values would be recorded.

4 CONCLUSION

The characterization of the kerf, made through roughness evaluation, proved to be an effective technique of investigation. Repetition of this experiment can be very satisfactory, provided that some parameters are carefully controlled. In particular, variation of the erosive power of the jet can play a key-role in activating some phenomenon. It is worth noting that jet power is not only dependent on the process parameters (water pressure, abrasive flow rate, etc.) but on equipment status (especially level of wear of the consumable components) as well. Moreover vibration proved to have a major impact on the kerf roughness, leading to very significant changes of such value.

REFERENCES

(1) H. Orbanic, M. Junkar, I. Bajsic, A. Lebar, An instrument for measuring abrasive water jet diameter, International Journal of Machine Tools and Manufacture, Vol. 49, 2009, pp. 843-849

(2) M. Hashish, Observations of wear of abrasive waterjet nozzle materials, Journal of Tribology, vol. 116, July 1994, pp. 439-444

(3) M. Nanduri, D.G. Taggart, T.J. Kim, A Study of Nozzle Wear in Abrasive Entrained Water Jetting Environment, Journal of Tribology, Vol. 122, Issue 2, 2000, pp. 465-471

(4) D.G. Taggart, M. Nanduri, T.J. Kim, F.P. Skeele, Evaluation of an accelerated wear test for AWJ nozzles, 9th American Waterjet Conference, 23-26 August, 1997, Michigan, pp. 239-250
(5) J.J. Rozario Jegaraj, N. Ramesh Babu, A soft computing approach for controlling the quality of cut with abrasive waterjet cutting system experiencing orifice and focusing tube wear, Journal of Materials Processing Technology, Vol. 185, 2007, pp.217-227
(6) M. Hashish, A Modeling Study of Metal Cutting with Abrasive Waterjets, Journal of Engineering for Industry, vol. 106, pp. 88-100, 1984
(7) M. Hashish, On the Modeling of Surface Waviness Produced by Abrasive-Waterjets, 11th International Symposium on Jet Cutting Technology, 1982
(8) J. Chao, G. Zhou, M.C. Leu, E. Geskin, Characteristics of abrasive waterjet generated surfaces and effects of cutting parameters and structure vibration, Journal of Engineering for Industry, Vol. 117, pp. 516-525, 1995
(9) M. Hashish, A Model for Abrasive-Waterjet (AWJ) Machining, Journal of Engineering Materials and Technology, Vol. 111, pp. 154-162, 1989
(10) M. Hashish, Material properties in abrasive waterjet machining, Transactions of the ASME, Journal of Engineering for Industry, Vol. 117, pp. 578-583, 1995
(11) L.P. McCabe, G.A. Sargent, H. Conrad, Effect of microstructure on the erosion of steel by solid particles, Wear, Vol. 105, pp. 257-277, 1985
(12) G. Maccarini, M. Monno, G. Pellegrini, C. Ravasio, Characterization of the AWJ kerf: the influence of material properties, 19th International Conference on Water Jetting, Nottingham, UK, October 2008
(13) L.M. Hlavàc, L. Gembalovà, I.M. Hlavacova, V. Màdr, J. Mèstrànek, Quality evaluation of the AWJ cutting through the declination angle, 19th International Conference on Water Jetting, October 2008, Nottingham (UK)
(14) J. Valìcek, S. Hloch, D. Kozak, Surface geometric parameters proposal for the advanced control of abrasive waterjet technology, International Journal of Advanced Manufacturing Technology, Vol. 41, 2009, pp. 323-328