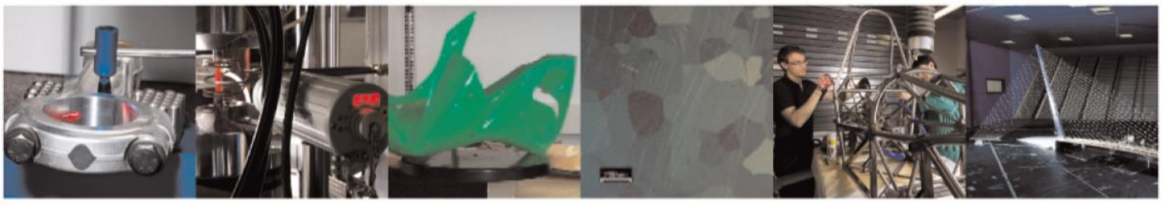

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Effect of workpiece heat treatment on surface quality of AWJ kerf

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1 Introduction

Abrasive water jet (AWJ) cutting is an advanced manufacturing technology used for machining hard to cut materials. The process do not generate heat as other processes such as laser or plasma, hence there are no heat-affected zones. This characteristic may be useful to cut materials for which heat may change their properties or when the specifications of the final application are especially restrictive.

A systematic study of erosive processes has been carried out since the late fifties. Finnie (1958) studied erosion phenomena at low attack angles (generally named 'cutting wear' when applied to AWJ), whereas Bitter (1963a, 1963b) studied impact at larger angles ('deformation wear'). Regarding AWJ application on metals, Hashish (1982, 1984) stated that both cutting and deformation wear may take place within the kerf and observed the effect of different types of wear. According to Hashish the kerf can be divided into two zones, placed at different distance from the jet entry surface. In the first zone of the kerf (having width hc), towards jet entrance, smooth surfaces are generated mainly by cutting wear at low impact angle. Such zone is always present on the kerf and its width hc may be extended to the whole thickness, otherwise the deformation wear zone (having width hd) is present, where the removal mechanism takes place with larger impact angles and a coarser kerf surface is observed. Actually, in the bottom part of the kerf some striations are often visible; striation formation was related to large impact angles by Hashish (1995).

The same author proposed mathematical models to evaluate the widths hc and hd, linking them to several cutting parameters, all related to the erosive power of the jet. In fact, in AWJ technology, the erosive power of the hydro-abrasive jet plays a key-role in the material removal process. Among the process parameters affecting erosive power, water pressure, abrasive flow rate and traverse speed of the cutting head are reported.

There are however others factors, not always easily measurable, that could have influence on erosive power (i.e., fluctuations of either pressure or abrasive flow rate, distribution of the abrasive mesh, wear of either nozzle or focusing tube, geometry of mixing chamber). For example, Hlavàc et al. (2010) studied the importance of internal shape of the cutting head on the particle disintegration in the mixing process with water jet and thus on erosive power of the jet.

Regarding the influence of material properties on the process, the presence of two different cutting zones suggests that there are also more than one material property that are relevant to the cutting process (Hashish, 1995). Several wear models have been made available in the literature for more than 50 years, wear mechanisms were acknowledged to differ as a function of the angle between jet and target surface.

For low impact angles, Finnie et al. (1967) presented a linear correlation between the reciprocal of the material hardness and the erosion rate. McCabe et al. (1985) found the effect of heat treatment on erosion resistance insignificant: the relative change in abrasive particle and target material hardness is very small. Hardness, strain rate sensitivity, grain orientation and size, thermal parameters were considered by Ruff and Wiederhorn (1979) the most important target material characteristics.

For large impact angle, deformation wear was modelled by Bitter (1963a, 1963b) who used an energetic approach and related wear resistance to material fracture strength. Combining the theories for cutting and deformation modes, Hashish (1989) presented a model for predicting the depth of cut of abrasive waterjet in different metals. Materials were characterised 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. As regards to the critical velocity, it can be related to material properties as in Bitter (1963a, 1963b) and was determined by best fitting the model to the experimental results.

In Hashish (1995), the effect of heat treatment and abrasive type on depth of cut was investigated. The research showed 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. A threshold hardness ratio, between material and abrasives hardness, 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. A relationship between maximum depth of cut h and material property was found:

$$h = \frac{A}{\sqrt{H}} + \frac{B}{E + C} \tag{1}$$

where A, B, and C are constants depending on AWJ parameters and the traverse rate, E is the modulus of elasticity and H is the Vickers hardness number. The equation expresses h as the sum of two terms, which are representative of the cutting wear zone and the deformation wear zone. In AWJ machining where the cutting wear mode is dominant, the cutting speed can be correlated with the hardness; the modulus of elasticity is a significant property in the deformation zone.

In literature experimental and analytical research efforts have been carried out to get predictive models for maximum kerf depth and for the obtained surface finish in AWJ cutting. 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 (Chao et al., 1995). Arola and Ramulu (1997) conducted an experimental study to determine the influence of material properties on the surface integrity and texture in AWJ machining of metals. In this work, geometrical surface properties are evaluated through the average roughness Ra and the profile skewness, while strain hardening is measured via microhardness tests. The microstructure of the workpiece proved to have effects on the cutting quality in terms of surface roughness and geometrical characteristics of the kerfs. The effect of workpiece material is represented in Zeng et al. (1999) by the material characteristic constant named ‘machinability number’. This number is connected with the hardness of the material: when the hardness of the workpiece increases, the machinability number decreases. The machinability number is contained in a semi-empirical equation that predicts the cutting speed to cut a certain depth with a quality level index. Brandt et al. (2000) developed an empirical model in order to propose a simple technological model to foresee the kerf depth and the cut surfaces roughness applied only for three reference materials (titanium, stainless steel and aluminum).

Validated theoretical models, developed by Hlavàc (2009), describe the curvature of the jet trajectory inside the kerf. These models predict the declination angle as a function of the depth (distance from the jet entry surface) and of overall cutting conditions, such as material properties, jet parameters and traverse speed. Strnadel et al. (2013) found a significant influence of material properties (hardness and inclusions in hardened steel) on the declination angle of striations on the AWJ cut surface. In particular, the mean size and the volume fraction of carbides proved to be relevant, as the increase in the declination angle with increased strength and hardness is caused by the lower degree of penetration of abrasive particles into the material during the interaction process.

In Maccarini et al. (2008), the authors reported that the effect of water quenching on the surface finish is strongly dependent on the material removal mechanism: in the cutting wear zone a higher workpiece hardness acts favourably on surface roughness while, in the deformation wear zone, this effect is reversed and the roughness of the kerf is worsened.

The aim of this work is to reproduce the above mentioned results performing a larger amount of repetitions, to allow variance analysis and to validate the consideration about the effect of material.

2 Experimental research

2.1 Set up

During the experimental research, the attention was paid to reproduce the same conditions in Maccarini (2008), in terms of cutting system and material. It is important to remark that a definition of ‘same condition’ is a critical aspect because many variables should be controlled, either related to the workpiece properties or to the process parameters or else to the system configuration. In particular while for the workpiece and process variables the reproducibility is quite assured, the control of systems variables proved to be a more complex issue. For instance, literature reports that the wear of nozzle and focusing tube has a significant effect on the results of AWJ cuts in particular as regard the surface roughness and the maximum thickness cut. In other words, the amount of wear on these components affects the erosive power of the abrasive jet. In Maccarini (2008), the experimental research was conducted using components of the cutting head having unknown wear. This situation is typical of the industrial manufacturing and, because of this, the reproduction of the experiments is not a trivial task. Since controlling each single process condition, including wear of components, is not practical, a suitable criterion for operational equipollence of different processes should be devised. Erosive power of the jet is a very good candidate for supplying such a criterion, provided that a suitable technique for measuring it is available.

2.1.1 Samples

Twelve samples, having 50 × 10 × 250 mm dimension, were parted by sawing longitudinal cuts from the same rolled bar. In each sample, two series of cuts were realised in a 'haircomb' fashion. The cutting length was 35 mm and the distance between kerfs was 5 mm. The workpiece used was carbon steel (C40 UNI EN 10083-2). It is worth noting that the specimens were derived from the same carbon steel bar, supplied in normalised state, used in Maccarini (2008).

In order to test materials having the same chemical composition (steel C40) but different hardnesses and microstructures, half of the samples were testes 'as is' (normalised) and others were water-quenched.

The water-quenched treatment was obtained through the following steps:

- Water quenching: the specimen was put in furnace at 840°C until fully converted in austenite. quenching in water followed
- stress relieving: this treatment was made in order to remove internal tension on the material; the sample was put in a furnace at 210°C for two hours. Then, the specimen was cooled slowly.

The hardness of the two different specimens, normalised and water-quenched, was evaluated by Vickers micro-hardness HV1000/15/15 and it was found to be, respectively, 235 HV and 519 HV, consistent with ASM (1991).

Metallurgical samples were polished and etched with Nital, to show microstructure. For normalised specimen, ferrite and pearlite structure is reported in Figure 1. Water-quenched structure is reported in Figure 2, showing martensite laths in a finer structure than Figure 1.

Figure 1 Micrography of the normalised sample

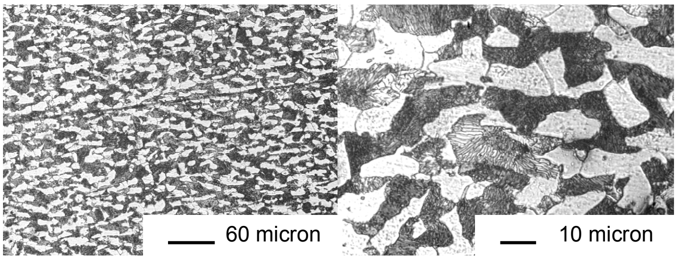
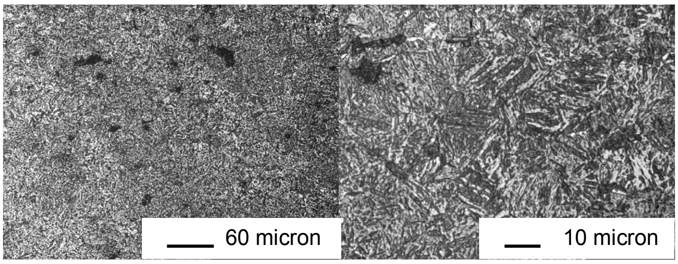


Figure 2 Micrography of the water-quenched sample



2.1.2 AWJ process parameters

The following process parameters were used for every experimental condition:

- diameter of nozzle: 0.3 mm.
- length of focus: 76 mm
- diameter of focus: 0.8 mm.
- condition of nozzle and focusing: new.
- stand off distance: 2 mm.
- abrasive: GMA Garnet, mesh 80.
- abrasive flow rate: 6 g/s.
- traverse rate: several values between 100 and 280 mm/min.
- water pressure: 300 MPa (campaign A) and 250 MPa (campaign B).

Traverse rate values were selected to range from low values, allowing good quality cuts, to an upper limit value beyond which complete parting of the kerfs (i.e. 'passing cut' condition) is not possible.

Passing cut limit traverse rates proved to be the same for both normalised and the water-quenched samples; this result is in accordance with Hashish (1995), stating that, when the workpiece hardness is much less than the abrasive material hardness, alterations by heat treatment become insignificant on the depth of cut.

As far as water pressure is concerned, two values were selected:

- 300 MPa (campaign A), same as in Maccarini (2008).
- 250 MPa (campaign B), this water pressure yields the same erosive power of the jet as in Maccarini (2008).

Appendix A reports in detail the methodology that was used to evaluate the erosive power of the abrasive waterjet and select a suitable pressure value.

2.1.3 System

AWJ cuts were realised using the equipment of the 'Non Conventional Technologies Laboratory' of the Dipartimento di Meccanica of the Politecnico di Milano (*Idro* produced by Tecnocut connected to the intensification system produced by Flow Int. Corp., Model *9XV*).

New nozzle and new focusing tube were used. This choice, different from Maccarini (2008), was made for sake of reproducibility because of the great influence of such components; moreover, the wear state of them can hardly be directly measured.

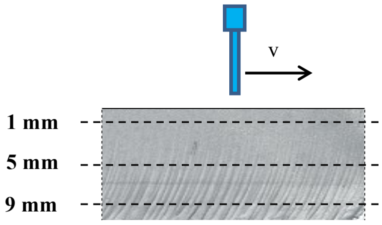
2.1.4 Experiment plan

The overall experimental plan includes three factors, namely material condition (two levels, normalised and water quenched), water pressure (two levels) and traverse rate (at least eight levels). Six repetitions were made for each set of experimental conditions and randomisation techniques were employed.

2.2 Surface data collection

The surface roughness of the kerf was measured to evaluate process performance, using a portable contacting surface measuring system (Diavite DH-5). Kerf roughness was described using the index Ra. The measurement system was set up with cut-off length of 2.5 mm and exploration length of 15 mm. Each roughness measure was evaluated by averaging four values, taking into account two factors: the probe travel direction (either same or opposite to the cutting head) and the side of the kerf. All tests were repeated six times, so each value is obtained from twenty-four different (although not all independent) measurements. The roughness was measured at different depths (1, 5, 9 mm from the entry surface) in order to include both cutting and deformation wear zone (Figure 3).

Figure 3 Depths of roughness measurements (see online version for colours)



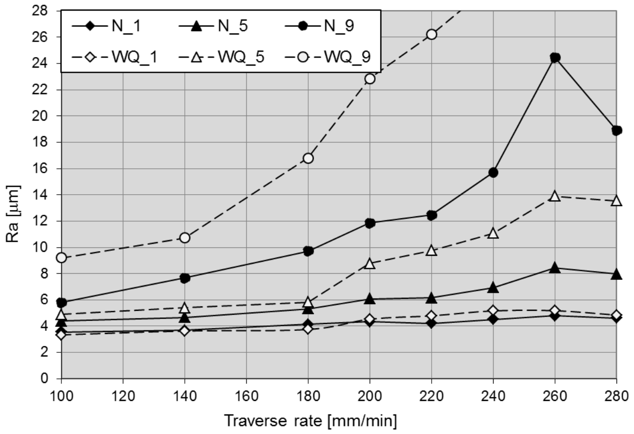
As a final result, roughness measurements were stored as records made of the following fields:

- experimental campaign (A or B, see 2.1.2)
- material heat treatment (normalised, quenched)
- traverse rate (7–8 values from 100 to 240 mm/min)
- depth of measurement (1–5–9 mm, refer to Figure 3)
- repetition number (integer from 1 to 6)
- measured side (right or left)
- probe travel direction (same as cut, opposite).

3 Analysis of the results

Figure 4 shows the average roughness Ra of the kerf obtained from experiments carried out at 300 MPa (campaign A) as a function of traverse rate. Two series of lines can be noticed, according to the metallurgical state of the specimens. Data from normalised samples (N) are shown as solid lines, water-quenched samples (WQ) are shown as dashed ones. Both N and WQ sets consist of three lines, corresponding to different depths of measurement (indicated with different markers).

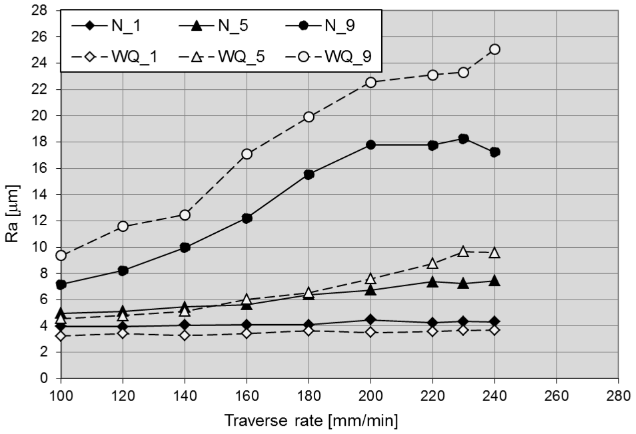
Figure 4 Ra as a function of traverse rate at different depths for the normalised (solid) and water-quenched (dashed) samples for 300 MPA water pressure (campaign A)



The roughness increases with both traverse rate and measuring depth, in accordance with the literature. Regarding the comparison between normalised and water-quenched samples, the surface finish for normalised samples is always better than for water-quenched ones. This difference is largest at maximum depth of measurement (9 mm, corresponding to the lowest erosive power of the jet), whereas with maximum erosive power (1 mm depth) it is negligible. For each measuring depth, the differences of roughness between normalised and water-quenched specimens generally increase with increasing traverse rate. Also in this case, a reduction of jet power (in this case induced by higher traverse rates) leads to larger roughness differences between material conditions.

Figure 5 shows the roughness of the kerf obtained from experiments carried out at 250 MPa (campaign B) as a function of traverse rate. It is worth remembering that this pressure value was chosen to reproduce the same erosive jet power as the experiments reported in Maccarini (2008).

Figure 5 Ra as a function of traverse rate at different depths for the normalised (solid) and water-quenched (dashed) samples for 250 MPA water pressure (campaign B)



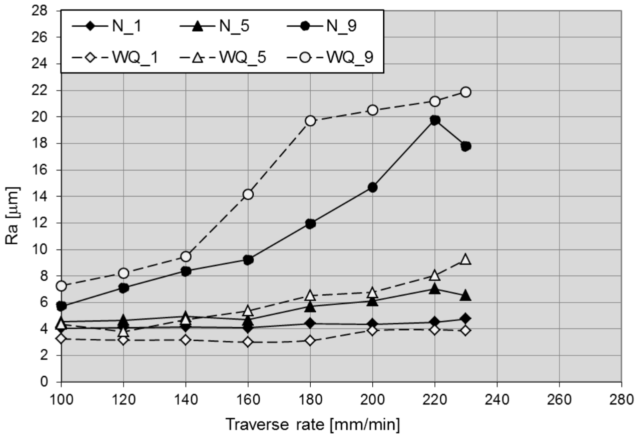
When water pressure of 250 MPa (campaign B) is used, complete separation of the kerf was found to take place using a lower cutting speed than with 300 MPa (campaign A).

Also in this campaign, when a single treatment (N or WQ) is considered, the effect of traverse rate and measuring depth is same as in Figure 4. In this case, however, in the cutting wear zone (i.e. measurements at depth of 1 mm) the harder sample (WQ) shows a better surface finishing than the normalised one. At low erosive power such behaviour is reverted. In other terms, in the cutting wear zone (top of the kerf), the hardness has a positive effect on the roughness surface of the workpiece; in the deformation wear zone (bottom of the kerf) higher values of hardness are connected to coarser surfaces. The difference between N_1 and WQ_1 roughness values (with depth of measurement 1 mm) is small and its significance requires statistical tests (Refer to Section 4).

In the transition zone (5 mm), the curves are close to each other and they cross at traverse rate of 150 mm/min. This behaviour is understandable, since this depth lies between two regions where hardness plays an opposite role: at higher traverse rates (i.e. lower jet power), the measurements taken at depth of 5 mm show the same pattern as for measurements at 9 mm depth, namely WQ samples have a smoother surfaces than normalised ones; conversely, when jet power is higher (lower traverse rates, smaller measuring depths), water quenched specimens show a slightly better surface (as at 1 mm depth).

This behaviour is similar as reported in Maccarini (2008) (shown here as Figure 6); both the general data pattern and the numerical roughness values show an excellent match. This effect can be explained by assuming that the wear of the components of the cutting head affects jet power as a reduction of water pressure does. Thus, using a worn focusing tube with water pressure 300 MPa may be considered as equivalent to using a new component and reducing the water pressure to 250 MPa. Besides, such statement is in agreement with the evaluation of the residual erosive power given in Appendix A and with the comparison of values of passing cut limit traverse rates between campaign B and Maccarini (2008).

Figure 6 Ra as a function of traverse rate at different depths of measure for the normalised (solid) and water-quenched (dashed)



Source: Samples obtained in Maccarini (2008)

4 Statistical analysis

Results of campaign B were evaluated through analysis of variance techniques to assess the significance of the results. The data collected are 324 observation of four variables, having roughness as response (mean of the above mentioned four measures of the same kerf) and traverse rate (V, nine levels), heat treatment (T, two levels) and depth of measurement (D, three levels) as input parameters. For each configuration six replications were made. It is worth noting that the experimental plan (Table 1) was set up to reproduce the data of Figure 6. In particular, traverse rate was varied on many levels. This plan is not optimised for standard analysis of variance (for this application, the number of levels should be small), so alternative analysis techniques were preferred.

Table 1 Experimental plan for all data sets

Factor	*# of levels*	*Values*
Traverse rate	8–9	From 100 to 280 mm/min
Heat treatment	2	N, WQ
Depth of measurement	3	1, 5 and 9 mm

Note: Refer to Figures 4, 5 and 6

A model having the following form was built:

$$\ln(R_a) = f(V_i, D_i, T_i) + \varepsilon_i \ldots\ldots i = 1,\ldots,324$$

First, the classical hypotheses on residuals ε_i were tested and validated. Residuals should be independent Gaussian random variables such that their expected value $E(\varepsilon_i) = 0$ and their variance $Var(\varepsilon_i) = \sigma^2$, independent from i. The assumption of constant variance (homoscedasticity) is the reason why a logarithmic transform of the response was taken into account; in this way the homoscedasticity assumption could be accepted (Bartlett, 1947).

In this experiment V is treated as a continuous quantitative variable, while T and D as qualitative ones; thus, ANCOVA (analysis of covariance) test was carried out (Sahai and Ageel, 2000). In fact, with respect to standard ANOVA, ANCOVA allows higher statistical power when large number of levels for a continuous variable are available.

A linear model, including all interactions, was set up:

$$\ln(R_a) = \beta_0 + \beta_1 V + \beta_2 D + \beta_3 T + \beta_{12} VD + \beta_{13} VT + \beta_{23} DT + \beta_{123} VDT + \varepsilon$$

ANCOVA results for the above mentioned model are reported in Table 2.

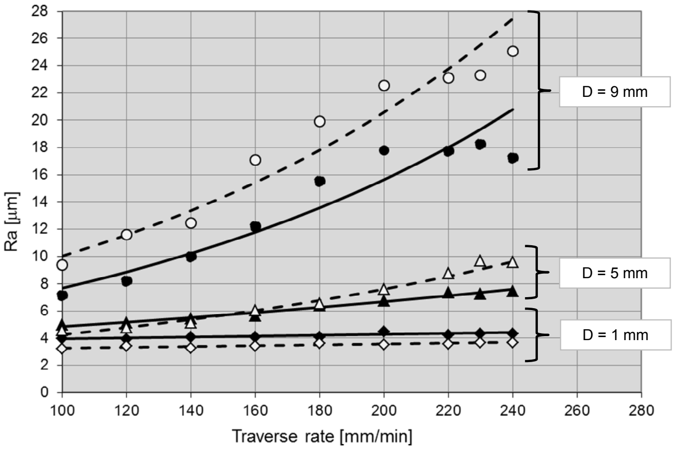
Table 2 ANCOVA for the complete model for ln (Ra)

	Df	*Sum sq.*	*Mean sq.*	*F value*	*Pr(> F)*
V	1	12.1229	12.1229	843.0268	0
D	2	102.9654	51.4827	3,580.1120	0
T	1	0.2711	0.2711	18.8553	0
V:D	2	4.7642	2.3821	165.6527	0
V:T	1	0.1671	0.1671	11.6180	0.0007
D:T	2	2.7571	1.3785	95.8638	0
V:D:T	2	0.2543	0.1271	8.8407	0.0002
Residuals	312	4.4866	0.0144		

These results give information about significance, expressed in terms of p-values, and relative importance, represented by the mean sums of square errors, of both the process parameters and their interactions. All input parameters and all their interactions proved to be significant. In particular, the effect of heat treatment (variable T) is proved to be significant, although to a smaller extent than the effect of either V or D (for this purpose, see the 'mean sq.' data column).

Figure 7 shows the behaviour of the regressive model as a function of traverse rate, compared with the experimental data, already reported in Figure 5. As it can be observed, according to the ANCOVA model water quenched samples are smoother at low depth D and rougher at high depth. This statement is statistically significant: all non-zero coefficients of the models are related to low p-values (lower than 2.5%). The overall effect is consistent with the assumption about two different material removal mechanisms (cutting and deformation) acting at different depths.

Figure 7 ANCOVA model for Ra (lines), compared with experiment (points) from campaign B (solid lines and black marks, water quenched; dashed lines and white marks, normalised)



5 Conclusions

The main goal of this work was to show how roughness of an AWJ kerf is affected by material metallurgical condition. Besides, the effect of microstructure and hardness of the workpiece proved to depend on the depth of measurement on the kerf.

In particular, the effect of hardness on the surface finishing is connected with material removal mechanism: in the cutting wear zone hardness acts favourably on the resulting surface roughness whereas, in the deformation wear zone when the hardness of the workpiece increases, the roughness of the kerf is worsened. An analysis of variance test validated the significance of this statement.

Furthermore, the erosive power of the jet proved to be a critical issue in assessing material effect. Smoother regions on hardened steel could not be observed when using any erosive power, in some cases material effect was almost negligible towards the top of the kerf. As a general rule, similar effects can be observed using similar erosive power.

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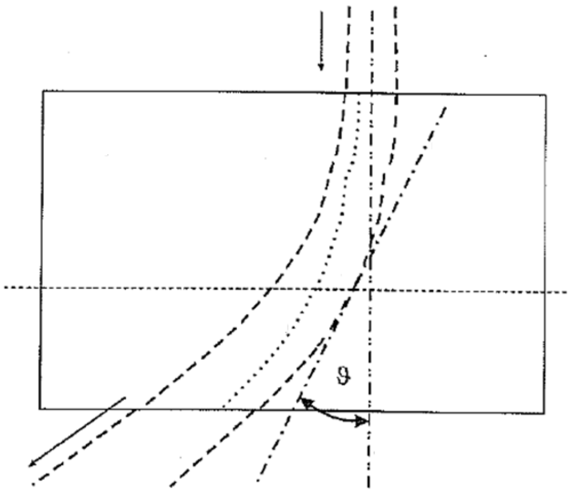
Appendix A

Assessment of the erosive power of the jet

A method for evaluation of the AWJ cutting quality (Hlavàc et al., 2009) is based on measurement of the depth dependent declinations of the tangents to a striation line from the impinging jet axis. At the entry of kerf, the jet is orthogonal to the material; increasing the depth of cut, the jet bends up to take an exit curvature opposite to the direction of the cutting head (Figure A.1).

Figure A.1 Scheme of the kerf evolution in the process of the abrasive liquid jet interaction with material



Source: Hlavàc et al. (2008)

The quality of the walls produced in the cutting process is therefore a function of declination angle. During the cutting process, curvature increases as the rate of volume removal decreases with increased depth of cut due to particle deflection, angle of attack reduction and particle deceleration (Hashish, 1989).

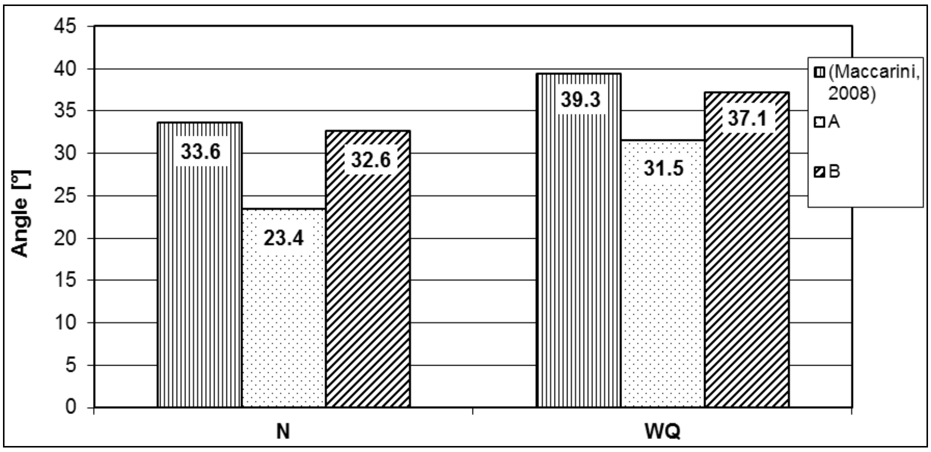
In any case, deflection angles are strictly linked to the residual erosive power of the jet. As a working assumption, it can be stated that the same exit angles are typical of jets with same residual density of energy. Since, under the same cutting conditions (geometry, material and process parameters) it is reasonable to assert that the same power has been required, one can conclude that the initial jet power (the sum of residual and required energy) was the same. Thus, exit angle could be used as a measure of jet power.

Using the exit angle evaluation, it is possible to assess the wear status of the cutting head components; such technique was exploited in the present paper. The angle between the tangent of the striation on the surface and the axis of the impinging jet was measured. To do this, some photographs were taken through an optical microscope; then the photographs were imported into a CAD package and the angles were graphically estimated. For every experimental condition, the angle was measured, in 20 points, on both sides of the kerf. Then, the final value was evaluated by averaging these measures.

Such technique was used to find out the cutting conditions for campaign B, aimed to reproduce a similar jet power as in (Maccarini, 2008); a suitable water pressure P was selected via trial and error until the exit angles were close to each other. The most suitable value of pressure was evaluated in P = 250 MPa.

Figure A.2 shows the comparison, in terms of declination angle, among the three experimental campaigns (reference (Maccarini, 2008), campaigns A and B), evaluated at a traverse speed of the cutting head of 200 mm/min. Exit angle data scatter was found to be small, no outliers were observed; for this reason it is possible to accept the presented results as a fairly reliable measure of a jet power, at least as a working assumption to select a suitable jet pressure for campaign B.

Figure A.2 Comparison between the angle declination measured on the samples obtained at 200 mm/min, campaigns A and B



Note: n: normalised samples; wq: water-quenched samples

Source: Maccarini (2008)

Angles declination of the jet for campaign B and (Maccarini, 2008) are similar while for campaign A, having an erosive power of the jet significantly greater than the others, the angle is lower.

It is worth mentioning that during campaign A full separation was achieved using higher speed of the cutting head (280 mm/min) than in the others cases (230 mm/min). This statement corroborates the previous remarks about differences in jet power.

When taking into account heat treatment effect, it can be observed that for the water-quenched samples the angle is always higher than for the normalised samples, so harder workpieces use slightly more jet energy. A similar result has been reported in Strnadel et al. (2013).