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Water Jet Peening of a Low-Alloy Steel by Means of a Standard Water Jet Cutting Machine Under Different Process Conditions

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Abstract: This work investigates the possibility to perform Water Jet Peening (WJP) by means of a standard Water Jet (WJ) cutting plant. The experimentation is carried out on 39NiCrMo3 specimens with the aim to find out the best working conditions of two different methods: the "in air WJP" and the "submerged WJP". Comparisons between the two methods and to previous experimentations in the reference literature are also presented.

Keywords: water jet, peening, residual stress

1 Introduction

The Water Jet Peening (WJP) is an alternative peening process where the plastic deformation and the residual stress on the surface of the workpiece are caused by the hammering effect of a high speed jet of water. The main challenge for this kind of process is to find out, on one hand, the correct combination of parameters in order not to exceed the limit of erosion, which would lead obviously to a failure, and, on the other hand, to obtain the best results on the workpiece in terms of achievable stress and thickness of the plasticized zone.

Moreover, two different methods have to be considered regarding the process set-up: the first one makes use of the water jet in air and the second one applies a submerged water jet configuration, which means that the jet and the workpiece are completely dipped under the water surface inside the catcher.

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2 Theoretical Background on Water Jet Peening in Air

2.1 Water Jet Characteristics and Morphology

As the jet exits from the orifice and propagates in the air, it is possible to distinguish three main regions (Figure 1), Yanaida, K.; Ohashi, A. (1978) and Yanaida and Ohashi (1980): the "initial region", the closest to the orifice, corresponds to the coherent portion of the jet, the "transition region", where the jet progressively loses its coherence due to friction with air and turbulence phenomena, which cause the formation of droplets, and the "final region" where the jet loses completely its coherence and is characterized by high divergence. The WJ peening must work in the transition region in order to obtain the best results, since this zone contains turbulent droplets with energy enough to obtain the hammering effect and the deformation of the target surface. Moreover, it is also important to guarantee a random impact of these droplets on the surface in order to produce an homogeneous effect; it is possible to increase the droplets formation thanks to the use of a mixing chamber and a focuser downstream the orifice. This components are needed in case of abrasive water jet (AWJ) cutting, but they are useful in this case, where no abrasive is employed ("pure water jet"), to disturb the jet coherence and enhance the droplets formation. The present work makes use of mixing chamber and focuser.

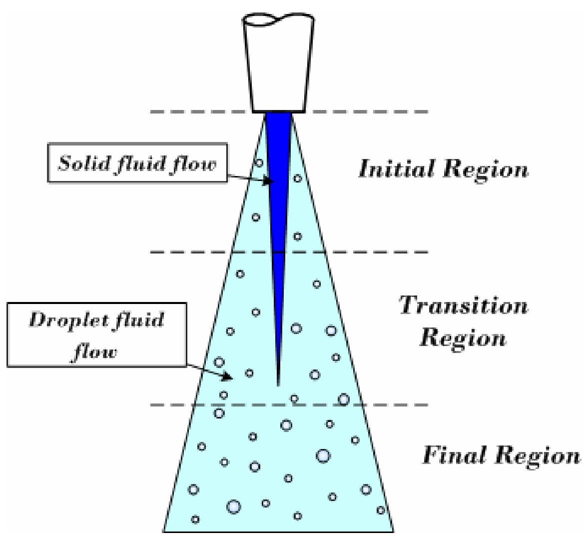

Figure 1: Morphology of a pure water jet in air Yanaida, K.; Ohashi, A. (1978); Yanaida and Ohashi (1980).

2.2 Deformation Model Proposed by Hashish

Modeling the impact of the jet droplets on the target surface is pretty complicated. Hashish proposed a simplified model Hashish et al (2005) based on the elastic-plastic theory that is able to relate the fluid characteristics to the process parameters with the aim of finding the maximum value of stand off distance (*SOD*), the distance between the focuser and the workpiece in the present case, which leads to a plastic deformation.

The geometry of the jet proposed by Hashish is shown in Figure 2; when the incidence angle θ is set to zero, the threshold value beyond which no plastic deformation occurs is given by:

$$\overline{SOD} = \frac{d_o}{2\tan\frac{\alpha}{2}} \left(\frac{3C_0}{CS_y} \cdot \frac{p}{f} \right)^{1/2} - 1 \tag{1}$$

where d_o is the diameter of the orifice, α is the divergence angle of the jet, C_0 is the velocity of sound in water, p is the water pressure upstream the orifice, f is the feed rate, S_y is the yield stress of the target material and C is a dimensionless constant depending on the impact geometry and usually evaluated by finite elements analysis.

The main drawback of this model is that it can predict the limit of the *SOD* working range but it can not find out its optimum value.

2.3 Specific Energy as a Comparison Parameter

A method to compare and analyze the efficiency of the WJ peening process in air consists in considering the "specific energy" transferred to the workpiece by the jet; this approach has already been applied during previous experimental campaigns at the Politecnico di Milano Motter (1998); Colosimo et al (2000). Hypothesizing the shape of the impact area as rectangular and a uniform pressure distribution along the whole surface of the impact zone, the specific energy can be calculated as:

$$e = \frac{qV^2n}{2f\delta} \tag{2}$$

where q is the water mass flow rate, V is the water velocity, n is the number of passes, δ is the pitch between two adjacent tracks and f is the feed rate.

3 Theoretical Background on Submerged Water Jet Peening

3.1 Process Characteristics

The process is carried out underwater in this case and it is also called "cavitation shot-less peening" because there's no more formation of droplets, while the defor-

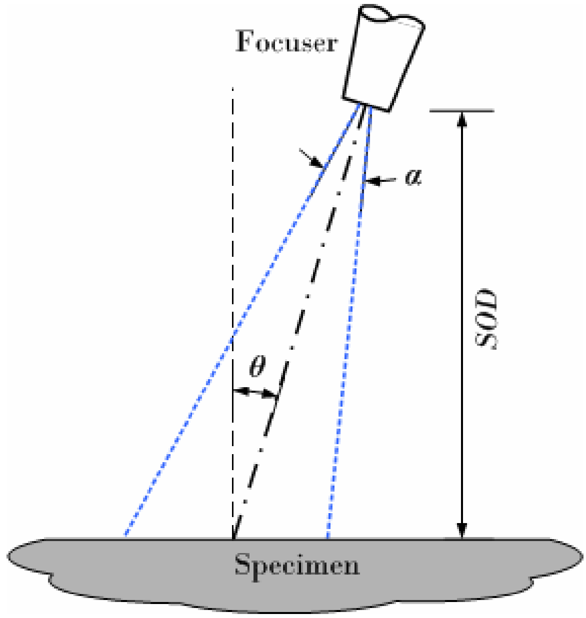

Figure 2: Geometry of the water jet in air Hashish et al (2005)

mation on the workpiece is caused by a jet of air bubbles which implode creating a compression effect at the impact. This process has been especially studied by Soyama Park et al (2000) and Macodiyo and Soyama (2006); the jet initially shows a coherent region close to the orifice (Figure 3); since this property progressively vanishes, as in the previous case, the operative region should be set downstream the coherent region in order to obtain the best peening effect on the workpiece, as shown in Figure 3.

Moreover, experiments carried out by Qin Ju et al (2006) showed that a further introduction of air in the mixing chamber improves results. In a standard WJ cutting machine, it is possible to introduce air in the water jet without controlling its flux: this can be done thanks to the Venturi effect obtained inside the mixing chamber (which is a standard component of an abrasive water jet cutting head, as already said) where the abrasive intake channel is kept open. This condition is applied in the present study.

3.2 Cavitation Number

One of the few theoretical parameters to evaluate the submerged process is given by Soyama Macodiyo and Soyama (2006); Odhiambo and Soyama (2003) and is called "cavitation number"; defining p as the water pressure upstream the orifice,

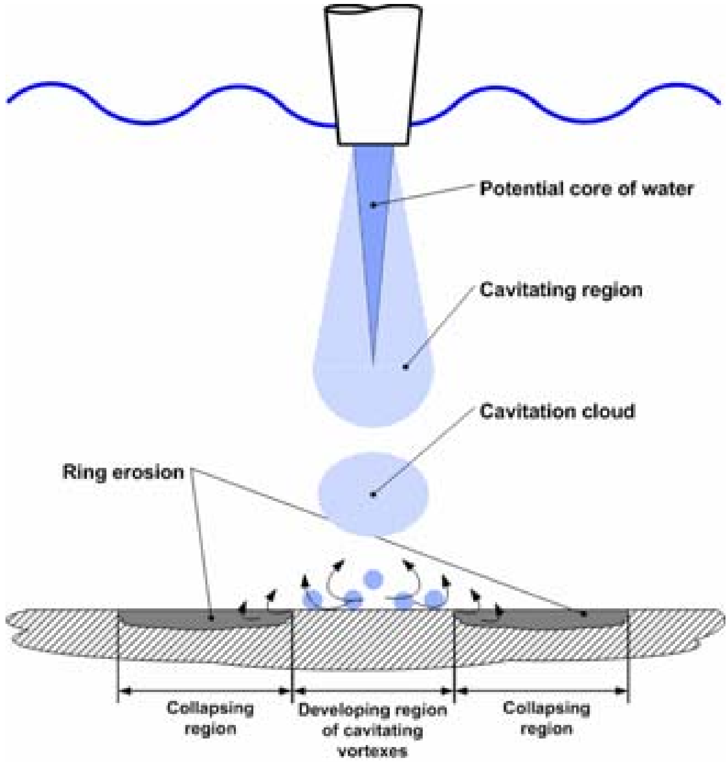

Figure 3: Morphology of the submerged water jet Park et al (2000)

p_c the water pressure surrounding the jet and p_v the vapour pressure, the cavitation number can be written as:

$$\sigma = \frac{p_c - p_v}{p - p_c} \approx \frac{p_c}{p} \tag{3}$$

since $p \leq p_c \leq p_v$, Macodiyo and Soyama (2006); Odhiambo and Soyama (2003). The value of σ indicated as the best is theoretically $\bar{\sigma} = 0.014$, which is achievable only if the chamber surrounding the jet is kept pressurized as in the case of Soyama's experiments. As it will be explained later, the maximum achievable value is just $\sigma \approx 0.001$ in our case.

3.3 Time as a Comparison Parameter

The method of the specific energy can not be applied to the submerged WJ peening because it was defined taking into account the physics of the water droplets which are not effective in this case. Instead, it is usually applied a definition of "equivalent time" given by Soyama Odhiambo and Soyama (2003):

$$t = n \cdot \frac{d_0}{f} \tag{4}$$

According to his experiments, a time threshold exists beyond which the residual stress does not increases.

4 Experiments on Water Jet Peening in Air

The experimentation carried out at the Politecnico di Milano has been performed on quenched and tempered 39NiCrMo3 steel specimens, subsequently stress relieved in order to reduce the residual stress and define a reference condition for the specimens. The general layout has also been designed to be compared with previous experimentations in literature Motter (1998); Colosimo et al (2000); Jenkins et al (2004); for this reason, most of the parameters are kept similar or equal to those experimentations where possible. Table 1 shows the comparison among the main parameters and results of each experimentation. Reference Colosimo et al (2000) has been placed in brackets in Table 1 since the reported parameters are compatible with the ones in Colosimo et al (2000) but not exactly the same.

Hashish experiments Jenkins et al (2004) present some important differences compared to the other ones: first of all, the use of a fan nozzle characterized by a different geometry from an orifice designed for cutting as the one employed in the present work, secondly, a different target material. Anyway, he states that the use of the focuser improves the effects of the peening treatment; the same result has also been confirmed by some trials made in the preliminary stages of this work.

The comparison to the studies Colosimo et al (2000) and Jenkins et al (2004) is more direct since such experiments were carried out at the Politecnico di Milano as well and on a steel with mechanical properties similar to properties of the target material of the present study. According to Motter (1998), the influence of the *SOD* seems not to be significant. This result is also investigated by the present work: this is the reason why the range of *SOD* variation is kept equal to the one reported by Motter (1998).

Mixing chamber openings are kept closed in order to avoid the air intake, the focuser is kept perpendicular to the surface (i.e. the incidence angle θ is set to zero) because this is the same position employed in the previous literature Hashish et al (2005); Motter (1998); Colosimo et al (2000) and previous trials carried out at the Politecnico di Milano verified this is the best position to maximize the impact energy; lastly, just one pass (n = 1) is carried out for each experiment.

The value of pressure is finally set to 100 MPa to be better compared to the ex-

Table 1: Comparison among the experimentations in literature on WJP in air and the current one

	Ref. Hashish et al (2005)	Ref. Motter (1998); Colosimo et al (2000)	Present study
Material	Al7075T6	C40 (steel)	39NiCrMo3 (steel)
d_o[mm]	0.3	0.3	0.3
Nozzle/Focuser	fan	standard	standard
p [MPa]	$103 \rightarrow 310$	$100 \rightarrow 300$	100
SOD [mm]	$24 \rightarrow 77$	$40 \rightarrow 70$	$40 \rightarrow 70$
f [mm/min]	762	$1000 \rightarrow 6000$	$150 \rightarrow 6000$
δ [mm]	/	0.5	0.5
θ [°]	0	0	0
Max. residual stress [MPa]	-150	-250	-303
Treatment penetration [μm]	250	/	20

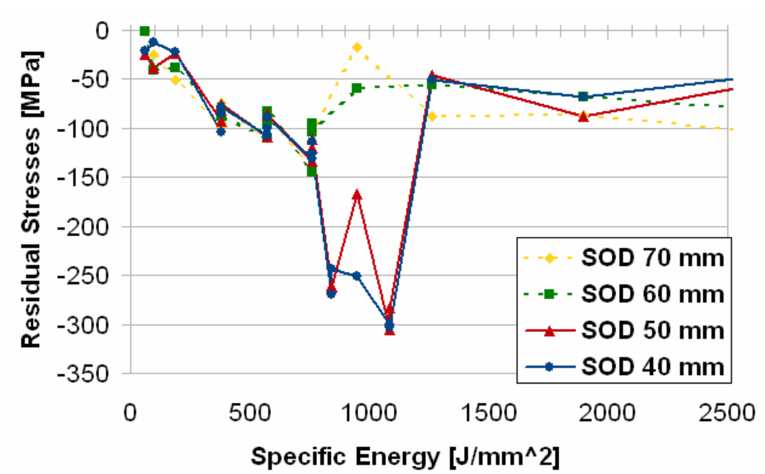

Figure 4: Results for WJP in air

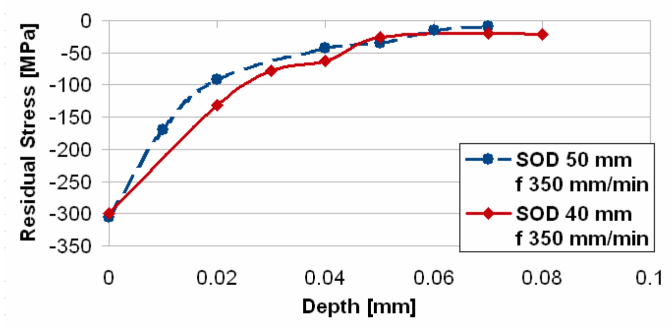

Figure 5: Residual stress distribution along the thickness for WJP in air

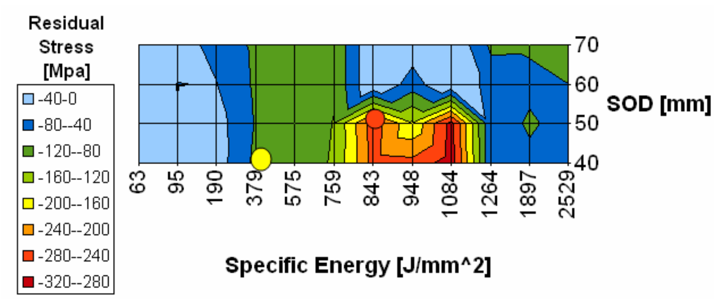

Figure 6: Residual stress map for WJP in air

perimentation regarding submerged WJ peening, where this is the chosen value, as explained later.

Just one replication is carried out for all the experiments. A check of the erosion occurred to the surface of specimens is performed by weighing them before and after the treatment.

4.1 Results

To study the state of residual stresses, XRD analysis of surface layer in the as-treated specimens is performed using an AST X-Stress 3000 X-ray diffractometer (radiation: Cr Kα, irradiated area: 1 mm^2, $\sin^2\psi$ method, diffraction angles (2θ) scanned between -45° and 45°) with X-ray exposure time of 30 s. For obtaining the trend of residual stresses, measurements were carried out in depth step by step removing a very thin layer of material using an electro-polishing device.

The obtained results are summarized by Figures 4 and 5.

It is clear that there is a well defined range of specific energy where the process effects in terms of residual stress are much more relevant, as it is pointed out by the peaks of the curves in Figure 4 referring to a *SOD* equal to 40 and 50 mm; for higher *SODs*, the effect seems to vanish: this fact underlines that the *SOD* is a significant parameter, contrarily to what the literature found out Motter (1998). The Figure 5 indicates also the trend of the residual stress along the measuring depth for two conditions (f = 350 mm/min and *SOD* equal to 40 and 50 mm) which are inside the range which gives the best results. It is also possible to plot the same data presented in Figure 4 in terms of the residual stress map as a function of the specific energy and the *SOD*, as shown in Figure 6: this kind of plot makes it more immediate to single out the area of the best working conditions, which are also summarized in Table 2.

Referring to the definition of the specific energy given in the Equation (2), the only parameter in this formula which varies during the present work is the feed rate f, consequently the ranges of specific energy e and feed rate f are completely equivalent.

Table 2: Best working ranges for WJ peening in air

Material	39NiCrMo3 (steel)
d_o[mm]	0.3
Nozzle/Focuser	standard
p [MPa]	100
SOD [mm]	40 → 50
f [mm/min]	350 → 450
Specific energy e [J/mm^2]	840 → 1090
δ [mm]	0.5
θ [°]	0
Residual stress [MPa]	-250 → -303
Treatment penetration [μm]	20

It is further possible to foresee the threshold of the *SOD* by means of the Equation (1); the process parameters' values for this calculation are selected inside the best working range reported in Table 2 and are summarized in Table 3 together with the other parameters required by the Equation (1).

The value of α is experimentally determined by relating the width of the kerf produced on an aluminium specimen to the *SOD*; the feed rate is set to 450 mm/min because this is one of the values giving the best results as pointed out before.

Substituting these values in the Equation (1), $\overline{SOD} \cong 53$ mm is obtained, which is actually consistent with the *SOD* values found to be the best ones in the present

Table 3: Parameters for the calculation of the threshold of the *SOD* according to the Equation (1)

α [°]	13
d_o [mm]	0.3
C_0 [m/s]	1500
p [MPa]	100
C	1.59
f [mm/min]	450
S_y [MPa]	540

study (Table 2); the red dot in the Figure 6 is representative of this result: notice that it is in the area where deformations (and residual stress) start rising up faster, even if deformations occur for higher *SODs* as well.

Moreover, the yellow dot in Figure 6 is representative of working conditions characterized by a higher feed rate; in particular, setting f = 1000 mm/min (e = 379 J/mm^2) and keeping all the other parameters unchanged, the Equation (1) gives a limit value of $\overline{SOD} \cong 40$ mm. In order to achieve higher residual stresses starting from the yellow dot of Figure 6, it is necessary to work at slower feed rates (higher specific energies) and/or at a lower *SODs*, in accordance to Hashish's criterion Hashish et al (2005).

Hashish's model therefore could be applied to estimate the operative range of the *SOD* parameter, but it is not able to point out the best working conditions.

The residual stress distribution along the thickness is shown in Figure 5: a substantial plastic deformation penetrates around 0.02 mm (Table 1), which is lower value than in case of the traditional shot peening process; moreover, the traditional peening produces the maximum residual stress below the surface while we observe a continuously decreasing exponential distribution in the present case.

5 Experiments on Submerged Water Jet Peening

The most important studies about this process have been carried out by Soyama [6, 9, 11, 12]; Table 4 shows the comparison among the main parameters employed by the present study and Soyama's one Odhiambo and Soyama (2003). Soyama's working conditions are pretty different because he performed experiments with a special nozzle in a submerged chamber kept under pressure in order to reach the optimum cavitation number which he found to be $\bar{\sigma} = 0.014$; this value is impossible to be obtained with a standard cutting machine, as the one employed in the present study, since the pressure surrounding the jet is approximately atmospheric and the minimum allowed working pressure is 100 MPa: inserting this parameters in the Equation (3) we obtain:

$$\sigma \approx \frac{p_c}{p} \approx \frac{101325\text{Pa}}{100 \times 10^6\text{Pa}} = 0.001$$

which is pretty far from Soyama's optimum.

Table 4: Comparison between experimentations on submerged WJ peening

	Ref. Odhiambo and Soyama (2003)	Present study
Material	CrMo Steel	39NiCrMo3 (steel)
d_o[mm]	1.8	0.3
p [MPa]	30	100
SOD [mm]	55	$30 \rightarrow 45$
f [mm/min]	/	$5 \rightarrow 90$
δ [mm]	/	0.5
Equiv. time t [s]	$0 \rightarrow 100$	$0.2 \rightarrow 3.6$
Number of passes n [-]	/	$1 \rightarrow 7$
Max. residual stress [MPa]	-560	-250
Treatment penetration [μm]	30	15

Specimens and process parameters are kept the same as for the experimentation in air, when possible, in order to carry out a coherent comparison between the two methods; the feed rate f has lower values than in air because the submerged process takes more time to be performed. The *SOD* values shown in Table 4 were found to be the best during preliminary experiments.

One replication is carried out for all the experiments. A check of the erosion occurred to the surface of specimens is performed as for the previous experimentation.

The surface roughness is then measured to verify its possible improvement in the submerged case, according to Soyama's studies Saito et al (2002). In order to confirm Qin's results Ju et al (2006), the effect of the air is investigated as well.

5.1 Results

In order to study the state of residual stresses, the same experimental procedure described in the Section 4.1 is applied. Figures 7 and 8 summarize the results of the experiments carried out in case of submerged WJ.

It is clear from Figure 7 that the obtained effects are not satisfying with a *SOD* of 30 mm, while the best results are related to the highest *SODs* and low equivalent

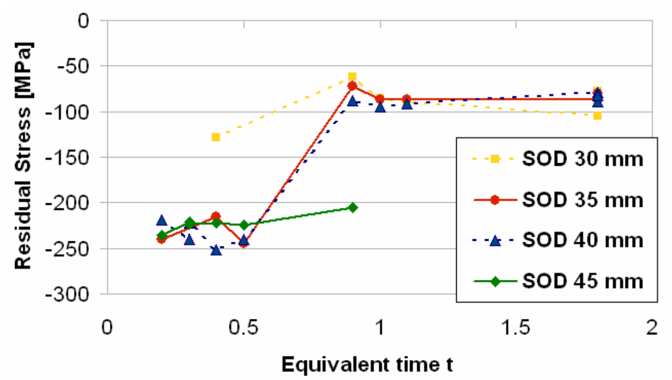

Figure 7: Results for submerged WJP with air intake

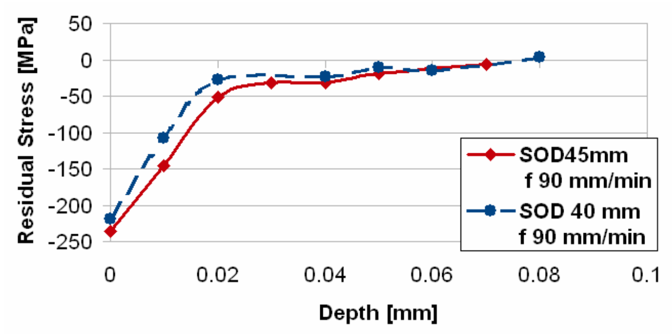

Figure 8: Residual stress distribution along thickness

times, which means, referring to the Equation (4), higher feed rates f and less passes n: this fact underlines that most of the plastic deformation occurs in the early instants of the process; carrying out many passes is then useless, which is a good point for productivity. The effect of these remarks can be clearly seen in Figure 9, representing the residual stress map as a function of the equivalent time and the *SOD*, where it is also possible to notice that the optimum area is wider than in the case of WJP in air (Figure 6), so that it seems to be easier to select parameters for this process.

Moreover, the highest reached values are slightly lower than in case of WJP in air. The Table 5 synthesizes the best working conditions.

Once the number of passes n is fixed to 1 (maximization of the productivity), referring to the definition of the equivalent time t given in the Equation (4), the only varying parameter is the feed rate f; as consequence, the ranges of equivalent time

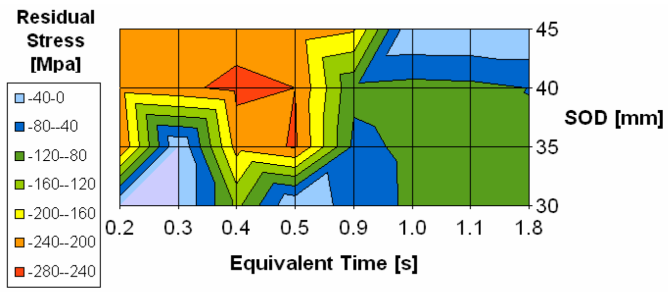

Figure 9: Residual stress map for submerged WJP with air intake

Table 5: Best working ranges for submerged WJP with air intake

Material	39NiCrMo3 (steel)
d_o[mm]	0.3
p [MPa]	100
SOD [mm]	35 → 45
f [mm/min]	35 → 90
δ [mm]	0.5
Equiv. time t [s]	0.2 → 0.6
Number of passes n [-]	1
Residual stress [MPa]	-230 → -250
Treatment penetration [μm]	15

t and feed rate f are completely equivalent.

The investigation on the residual stress distribution along the thickness (Figure 8) shows that the plasticized zone is around 0.015 mm, which is even less than the one obtained by WJ peening in air; Soyama's work pointed out a value around 0.030 mm. Moreover, also in this case, the maximum residual stress is found to be on the surface, as in case of WJP in air and in agreement with Soyama's remarks Ju et al (2006); Saito et al (2002).

Figures 10 and 11 summarize the results of the investigation about the effect of the air intake: good results are obtained without air intake for lower *SODs* (Figure 10), while, in presence of air, the best effects are achieved with higher *SODs* and lower equivalent times, which are also the best conditions to work with (Table 5).

These results add to previous studies carried about the effect of the air intake Ju et al (2006) and show how it can be beneficial to the submerged WJP process, especially in a certain range of *SOD*s.

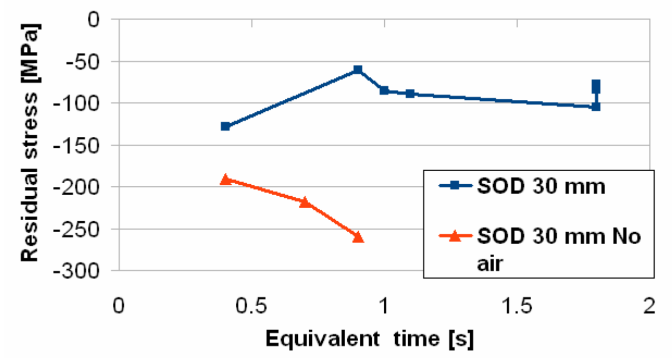

Figure 10: Comparison between submerged WJP with and without air intake (*SOD* = 30 mm)

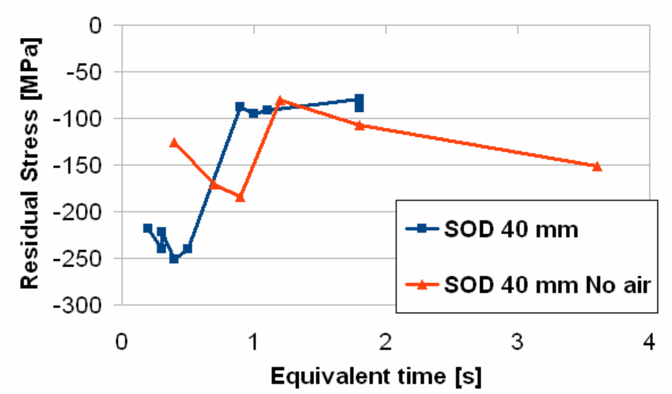

Figure 11: Comparison between submerged WJP with and without air intake (*SOD* = 40 mm)

Finally the investigation about the improvement of the surface roughness is presented in Figures 12 and 13.

An improvement of the surface average roughness is detected, especially without air intake (Figure 13); the interesting point is that there is a significant improvement also with air intake (Figure 12), particularly in the area of the best working conditions in terms of residual stress (Table 5): this fact could partially compensate the disadvantageous effect of having a thinner plasticized thickness: as a matter of fact, a better roughness theoretically improves the fatigue resistance, even if further experimentations is needed to support this consideration.

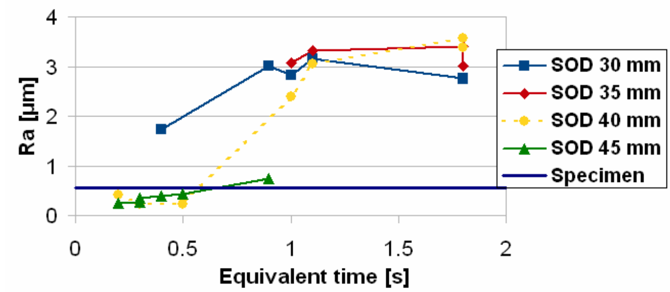

Figure 12: Investigation on roughness improvement in case of submerged WJP with air intake

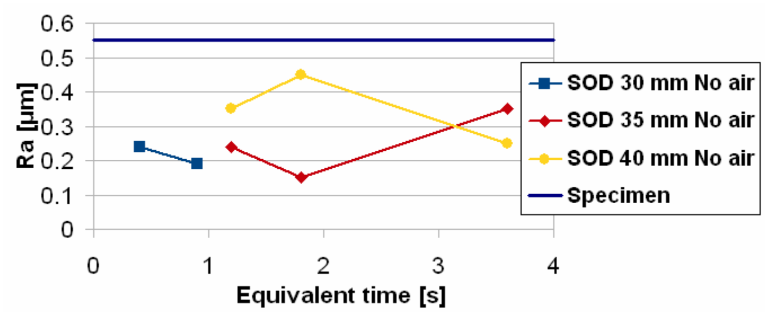

Figure 13: Investigation on roughness improvement in case of submerged WJP without air intake

6 Conclusions

Experimentations carried out in the present study demonstrate how WJ peening is feasible employing a standard WJ cutting machine as the achievable residual stress is significant. The two different proposed methods are slightly equivalent in terms of achieved residual stress and optimum *SOD*, even if the "in air" process allows higher feed rates and consequently a better productivity. On the other hand, the submerged process is easier to calibrate as the optimum is obtained in a wider range of parameters, while the in air process needs much more trials to be correctly set. The main disadvantage of both methods is the thickness of the obtained plasticized zone which is an order of magnitude lower than in case of standard peening processes.

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