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EXECUTIVE SUMMARY OF THE THESIS

Towards the modelling of abrasive slurry jet processes through a synergistic numerical-experimental approach

LAUREA MAGISTRALE IN MATHEMATICAL ENGINEERING - INGEGNERIA MATEMATICA

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1. The engineering problem and the scope of the thesis

Cutting is one of the fundamental processes in the mechanical industry. The traditional techniques (milling, turning, drilling) allow to machine a wide range of sizes and shapes, but usually require an expensive equipment, a demanding setup and a long working time. In addition, cutting tools wear and heating are non-negligible drawbacks, that affect both the quality of the process and the durability of the system.

An increasing interest has risen in non-traditional cutting techniques, such as Abrasive Water Jet Machining (AWJM). This technology uses a high-pressure fluid flow, mixed with a solid particle phase and it has been widely applied, for instance, in the micro-mechanical industry, as it involves small forces, minimizing the risk of fracture for small, fragile components. To improve machining quality, Abrasive Slurry Jet Machining (ASJM) techniques have been developed, that employ a uniformly mixed two-phase flow, called slurry, resulting in a more uniform abrasive action and more accurate cutting.

The numerical simulation has great potential for the optimized design of ASJM, with regard to both the equipment and the manufacturing process. However, this requires disposing of a simulation framework capable in describing the complex physical phenomena ad the basis of ASJM. In this regard, two particularly challenging features are the modelling of the slurry flow and the estimation of the material removal produced by the impact of the solids against the target wall, i.e. the slurry erosion. The present thesis aims at providing a contribution in relation with the latter of the two features here above. In particular, improvements were made to a methodology for the calibration of erosion models based on a combined CFD experimental approach, called SAER (Surface Aided ERosion prediction), subject of recent research of the supervisor and his collaborators.

2. Numerical prediction of slurry erosion

Solid particle erosion is a complex physical phenomenon, that involves both a macroscale, the flow dynamics, and a microscale, encompassing particles' interaction, particle-wall impacts and fracture mechanics. Therefore, accurately studying the erosion process is a non-trivial task. The modelling of slurry erosion is generally carried out following a two stages procedure. Firstly, the slurry flow is simulated using an Eu-

lerian Lagrangian model, in which the flow field is solved in a cell-based framework, while the solid particles are tracked singularly, by solving their associated equation of motion. Afterwards, an erosion model is applied to estimate the material removal caused by the individual particle-wall impingements.
Most erosion models are empirical in nature, and they are obtained by fitting the results of a typical benchmark test called Dry Direct Impact Test (D-DIT). In a D-DIT, a compressor accelerates the air flow, that is driven to the specimen through a pipeline system. A particle-feeder provides the abrasive medium to a mixing area, where it gets dispersed in the flow. The mixture, then, exits through the nozzle, impacts the workpiece and is collected in a discharge zone. In such tests, given the low density of air, the particles' motion is mainly driven by inertia. This implies that the particles impact the specimen surface at an angle that can be approximated with the inclination of the nozzle with respect to the specimen. A rough estimate of the impact velocity could be performed by approximating it with the jet outlet velocity, but this would not consider the slip actually present between air and solid particles.
One of the most widely used empirical erosion models obtained from D-DITs is the one proposed by Oka et al. [1] in 1997. According to this model, the erosion ratio ER, defined as the ratio between the total mass loss and the total mass of abrasive particles, for impacts happening at any angle θ, by multiplying the erosion ratio at normal impingement by an impact angle function $f(\theta)$ given by

$$f(\theta) = a(sin(\theta))^b \left(1 + H_v \left(1 - sin(\theta)\right)\right)^c \quad (1)$$

where H_v is the target material Vicker's hardness, while a, b and c are the empirical coefficients obtained by fitting the experimental results of D-DITs.
One of the main issues of erosion models obtained from D-DITs is that they are calibrated at particle impact velocities which are significantly higher than those encountered in slurry erosion. Thus, an alternative method was proposed to develop erosion models specifically intended for slurry conditions. This method makes reference to an alternative benchmark case to D-DITs, which is the Wet Direct Impact Test (W-DIT).

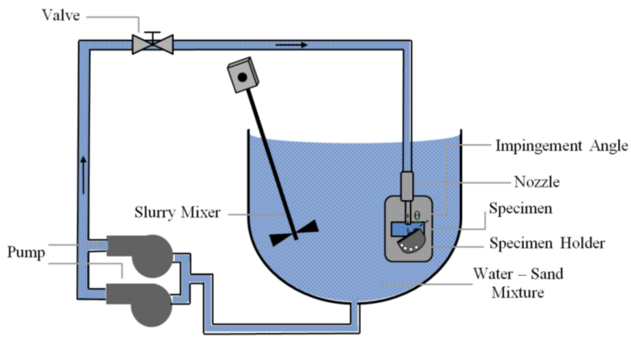

Figure 1: Diagram of a submerged W-DIT.

In a W-DIT, sketched in Fig.1, the carrier fluid is a liquid, typically water. Owing to the key role played by drag, the range of particle impact velocities and particle impact angles is wide, therefore these properties cannot be easily estimated from the jet velocity and the nozzle-to-specimen inclination angle. However, this information could be obtained by performing a CFD simulation of the slurry flow. In a W-DIT, the erosion depth distribution could be measured using profilometers or microscopes. Reproducing the same experiment through CFD could provide the particles' impact statistics, namely velocity, inclination and location. The basic idea of the SAER method, subject of this thesis, is to combine the experimental and the CFD-based information to determine the coefficients of an erosion formula with appropriate mathematical form.

3. Mathematical models

The numerical simulations performed in this thesis were carried out in Ansys Fluent 2022. In the Eulerian-Lagrangian modelling , the one-way coupling regime assumption is made owing to the low value of particle concentration in the reference experiments [2],[3]. Thus, the flow field without particles was calculated first and, afterwards, the trajectories of the particles are calculated one after the other. The two test cases considered refer a submerged slurry jets (first case) and to free slurry jets (second case). For the calculation of the fluid flow in the first case, use was made of a single-phase model. The Reynolds-averaged Navier-Stokes equations (RANS) were solved, adopting the $k-\varepsilon$ Raelizable turbulence model and the Scalable Wall Function approach for near-wall treatment. In the second case, the

Volume Of Fluid (VOF) model was used to simulate the free water jet in air. Also in this case, a RANS-like formulation of the VOF was solved and the same turbulence model as the previous case was employed.
The solid phase motion has been computed by solving an equation of the form Eq.2 for each particle, where $\mathbf{x}(t)$ is the particle's trajectory $\mathbf{v} = d\mathbf{x}/dt$ is the instantaneous velocity, m_p is the particle's mass, $\mathbf{F}_m$ is the sum of mass forces, $\mathbf{F}_{fp}$ represents the action of the fluid on the particle

$$m_p \frac{d\mathbf{v}}{dt} = \mathbf{F}_m + \mathbf{F}_{fp}. \tag{2}$$

The only relevant mass force in the reference application was the gravitational force, while the action of the fluid on the particle considered the contributions of the drag, buoyancy, lift, pressure force, and virtual mass can be rewritten as Eq. 3

$$\mathbf{F}_{fp} = \mathbf{F}_{drag} + \mathbf{F}_b + \mathbf{F}_p + \mathbf{F}_{vm} + \mathbf{F}_{lift} \tag{3}$$

with buoyancy force F_b, pressure force F_p, given by the pressure field gradient and virtual mass force F_{vm}, which reproduces the force needed to accelerate the fluid surrounding the particle.
As already mentioned, the basic idea of the SAER method for erosion model calibration is to combine the particle impact velocity and particle impact angle provided by the numerical simulation with the erosion scar measured in the W-DIT test. The erosion model is then obtained by fitting the chosen correlation to the experimental data.
Specifically, the sample surface is divided into small cells and, in each cell i, a function F for the erosion ratio of that cell, ER_i, is defined. Note that, for normally impinging jets, it is natural to define cells by splitting the sample surface into concentric rings, which is procedure followed in this thesis.
Assuming that the function F can be written as the product of an impact velocity function (usually modelled as a power law with exponent n) and an impact angle function $f(\theta)$ and including the influence of other physical parameters in a multiplicative coefficient K, the erosion ratio can be written as

$$ER_i = K\, \bar{v}_{p,i}^{n}\, f(\bar{\theta}_i) \tag{4}$$

where $\bar{v}_{p,i}$ is the average particle impact velocity magnitude and $\bar{\theta}_i$ is the average impact angle, computed on cell i.
After some mathematical manipulation, the product between constant K and the impact angle function can be seen as a function of known quantities and its value can be easily computed for each cell (Eq. 5)

$$K\, f(\bar{\theta}_i) = \frac{\rho_t\, S_i\, h_i}{N_p\, \dot{m}_p\, t\, |\bar{\mathbf{v}}_{p,i}|^n} \tag{5}$$

where h_i and S_i are the erosion depth measured in cell i and its surface area, ρ_t is the target material density, $\dot{m}_p$ is the mass flow rate associated to the particle trajectories in the "parcel" framework and N_p is the number of particles impacting on cell i. The velocity exponent n was initially kept constant, as also done by Mansouri et al. [2], [4]. Finally, the impact angle function can be obtained by fitting, thus finding the mathematical model suited for the experimental depth measures. In Messa et al. [5], use was made of the impact angle function of the model by Oka et al. (Eq. 1), thereby determining the parameters a,b, and c.

4. Application of the original SAER method to the first test case

The first test case analysed in the thesis was reported in [3], concerns a W-DIT experiment involving a mixture of water and glass beads impacting on an aluminium sample. Following the nomenclature reported in [3], an erosion equation was calibrated based on the experimental data of case 1. Then, three normal impact tests involving glass beads of increasing diameter, namely case 5, case 12 and case 20, were used for the validation of the calibrated equation. The main properties of the tests are summarized in Table 1, where d is the particle diameter and V_{jet} is the jet velocity magnitude.
The same analysis was repeated here with the purpose of verifying the existing methodology. After calculating the single-phase water flow field, the particles' trajectories were computed via the Discrete Phase Model (DPM) available in Ansys Fluent. After tracking down each particle, its velocity components at the moment of impact on the sample surface were calculated

during the post-processing phase. The selected number of injected parcels, following a sensitivity analysis, was 50000. The sample surface was split into 20 concentric rings.

	$d\,[\mu m]$	t [min]	$V_{jet}[m/s]$
case 1	90	60	35.97
case 5	120	45	33.54
case 12	250	45	35.69
case 20	350	45	35.98

Table 1: Experimental settings for the reference tests.

Following the approach described in Section 3, these impact properties were used to fit an erosion equation of the type in Eq.1, to the experimentally measured erosion profile [3], selecting $n = 2.1$. The values of the coefficients of the impact angle function obtained from regression are reported in Table 2

a	b	c	R^2
$5.183 \cdot 10^{-10}$	0.7204	2.298	0.78

Table 2: Calibrated coefficients.

The calibrated erosion model was then applied to the erosion prediction in test 5, 12 and 20 (case 12 and 20 are shown, by way of example, in Fig. 2-3).

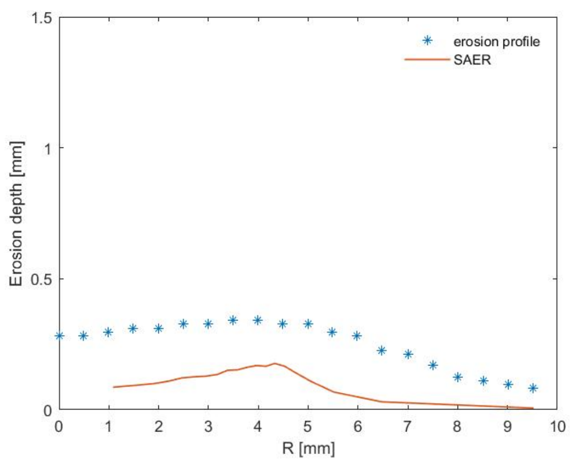

Figure 2: SAER performance in case 12.

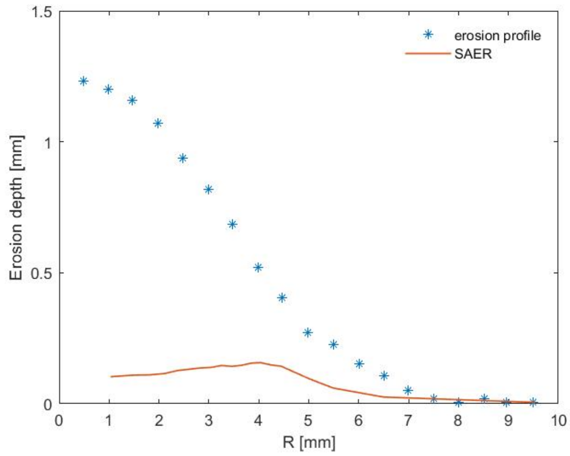

Figure 3: SAER performance in case 20.

Since the erosion prediction accuracy dropped significantly in the cases with bigger particles, possible ways to improve the calibration procedure were explored, as explained hereafter in Section 5.

5. Improvements to the SAER procedure

As a possible way to improve the erosion prediction accuracy, the velocity exponent n was included among the calibration coefficients. This is also aimed at generalizing the procedure to cases where no hint at a suitable value for n can be inferred from the literature.
Two sets of calibrated parameters are presented, Set 1 has been obtained by only allowing for positive values of the coefficients, while set 2 was found having no limitations on the possible attained values. Set 1 in Table 4 shows really close values to those previously obtained (Paragraph 4), so it is not surprising that it did not noticeably improve the erosion prediction, but it is relevant to notice that this results upholds the suggested value of 2.1. An interesting behaviour was instead observed using a second set of coefficients (set 2). The calibrated impact angle function does not show the typical observed trend, with an early peak followed by a gradual decrease for higher impact angles, while the velocity exponent n is much larger than 2.1. This implies that the found equation is fully empirical in nature, but the erosion prediction performance improves significantly.

	a	b	c	n
set 1	$1.791 \cdot 10^{-10}$	0.8093	2.701	2.391
set 2	$3.184 \cdot 10^{-11}$	0.61	-1.236	3.55

Table 3: Fitting coefficients.

The erosion prediction capability of the model for case 12 and case 20, adopting the coefficients in set 2, is shown in Fig 4 - 5.

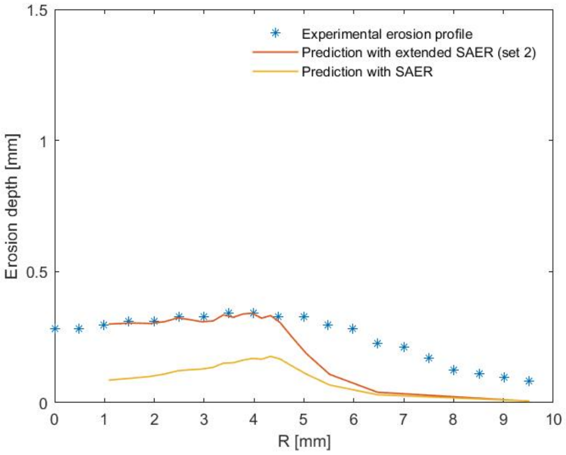

Figure 4: Extended SAER performance in case 12.

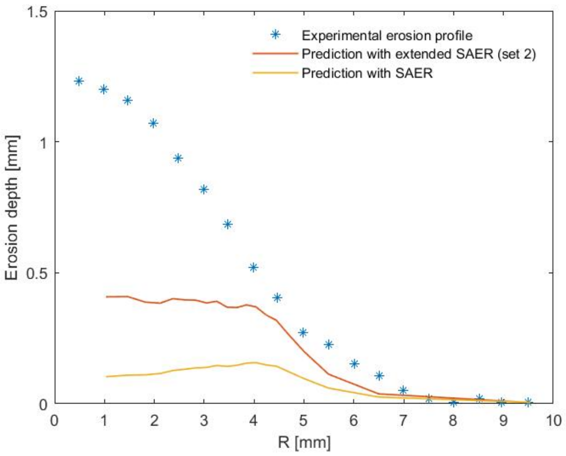

Figure 5: Extended SAER performance in case 20.

A different way of modifying the procedure could be to select a different model for the impact velocity function. Lester et al. [6] have questioned the power law impact velocity model used so far and proposed a different function (Eq. 6)

$$g(\mathbf{v}) = g_0\mathbf{v} + g_1\mathbf{v}^2 + g_2(e^{g_3\mathbf{v}} - 1) \qquad (6)$$

This model has been included in the fitting session and the resulting equation has been applied to cases 12 and 20. The results in case 20 are shown in Fig. 6.

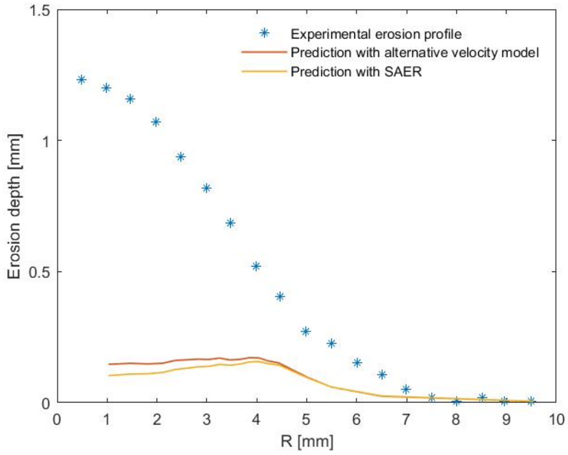

Figure 6: SAER performance in case 20 (velocity function modelled as in Eq. 6).

A slight improvement of the erosion prediction capacity of the method can be observed, but the simpler mathematical structure of the power law previously adopted seems to be a more sensible choice, as it requires just one parameter to be calibrated. Thus, the new SAER methodology still uses the power law velocity function, but it includes the power exponent among the calibration coefficients.

6. Application to a second test case

The combined approach has been applied to a second test case. Experimental data on a free slurry jet test involving garnet grains impacting on a small stainless steel (SS304) sample were provided by the research lab of prof. Marcello Papini from Ryerson University (Canada). The stand-off distance was 1 mm, the nozzle diameter 254 μm, the operating pressure equal to 137 MPa, corresponding to an approximate fluid speed at the nozzle outlet of 192 m/. The dwell time of the experimental test used for calibration was 100 ms. Unlike those of the previous first

test case, the flow conditions of the second test cases are typical of ASJM processes and, thus, they allow for the verification of the methodology in the context of this manufacturing technique.
As already mentioend, the Volume of Fluid model (VOF), was applied to handle the two-phase (air-water) flow, and the particle tracking was performed over the VOF solution. The calibrated coefficients of the erosion model, inclusive of the velocity exponent n, are reported in Table 4.

a	b	c	n	R^2
$5.5 \cdot 10^{-08}$	4.496	4.421	3.007	0.83

Table 4: Fitting coefficients.

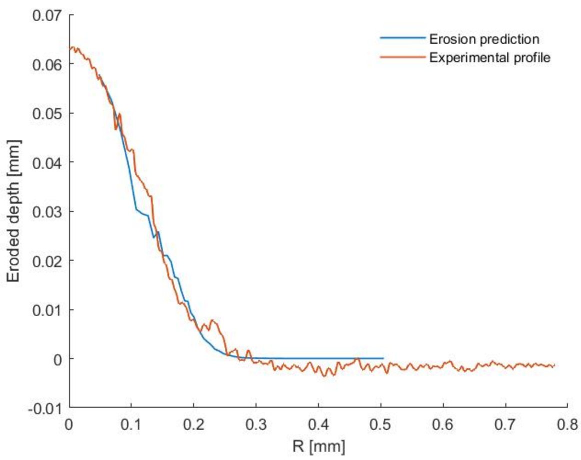

Figure 7: Extended SAER profile for the calibration case.

As shown in Fig. 7, the erosion equation reproduces the experimental profile used for its calibration accurately.
This study has allowed applying the extended SAER procedure to a free slurry jet, that closely represents the actual operating conditions in ASJM. Even though it was not possible to validate the resulting equation, since the calibration test was the only one available, the results are positive and the application of this method to modelling abrasive slurry jets appears promising.

7. Conclusions

The presented study has regarded the implementation and possible improvements of a combined numerical-experimental methodology for the calibration of empirical erosion models for the prediction of slurry erosion. This is an essential step towards the development, as a long-term goal of this research, of a CFD-based framework for the simulation of Abrasive Slurry Jet Machining (ASJM) processes.
Two test cases have been studied, that differ in both geometrical features, operating flow conditions and involved materials. The SAER formulation initially considered, proposed by Mansouri et al. [2] and further developed by Messa et al. [5], yielded accurate erosion prediction results compared to traditionally used models. However, it failed in correctly capturing the effect of particle size on erosion. In order to overcome this limitation, the use of a different impact velocity function was explored, but the results were only slightly improved. Conversely, the inclusion of the velocity exponent of the erosion model in the fitting process led to even better results. Particularly, the comparison against slurry experiments performed at the research lab of prof. Marcello Papini from Ryerson University (Canada) proved, for the first time, that the improved SAER methodology is potentially applicable also for the flow conditions of interest to ASJM processes.

8. Acknowledgements

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References

[1] Y.I. Oka, H. Ohnogi, T. Hosokawa, and M. Matsumura. The impact angle dependence of erosion damage caused by solid particle impact. *Wear*, 203-204:573–579, 1997. ISSN 0043-1648. doi: https://doi.org/10.1016/S0043-1648(96)07430-3. URL https:

//www.sciencedirect.com/science/article/pii/S0043164896074303. 11th International Conference on Wear of Materials.

[2] Amir Mansouri, Hadi Arabnejad, Siamack Shirazi, and Brenton McLaury. A combined cfd/experimental methodology for erosion prediction. *Wear*, pages –, 12 2014. doi: 10.1016/j.wear.2014.11.025.

[3] Yongbo Wang. *A modelling framework for slurry erosion prediction through Computational Fluid Dynamics simulations*. PhD thesis, Politecnico di Milano, 7 2021.

[4] Amir Mansouri. *A combined CFD-experimental method for developing and erosion equation for both gas-sand and liquid-sand flows*. PhD thesis, University of tulsa, The address of the publisher, 7 2016.

[5] Gianandrea Vittorio Messa, Yongbo Wang, Marco Negri, and Stefano Malavasi. An improved cfd/experimental combined methodology for the calibration of empirical erosion models. *Wear*, 476:203734, 2021. ISSN 0043-1648. doi: https://doi.org/10.1016/j.wear.2021.203734. URL https://www.sciencedirect.com/science/article/pii/S004316482100123X. 23rd International Conference on Wear of Materials.

[6] D.R. Lester, L.A. Graham, and J. Wu. High precision suspension erosion modeling. *Wear*, 269(5):449–457, 2010. ISSN 0043-1648. doi: https://doi.org/10.1016/j.wear.2010.04.032. URL https://www.sciencedirect.com/science/article/pii/S0043164810001912.