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STUDY ON THE APPLICABILITY OF COUPLED EULERIAN-LAGRANGIAN FORMULATION IN ABRASIVE WATERJET MACHINING SIMULATIONS

Abstract: *Non-conventional machining processes are considered as reliable alternatives to the established conventional ones in the case of processing of difficult-to-cut materials. Especially, Abrasive Waterjet Machining (AWJM) is advantageous for this purpose, as it can handle a wide range of workpiece materials and does not cause heat affected zones. In order to study the phenomena occurring during AWJM, numerical simulations should be carried out along with experiments. As machining processes involve significant material deformation, Coupled Eulerian-Lagrangian (CEL) Finite Elements (FE) models have been proven significantly accurate for this purpose, compared to pure Lagrangian models. Thus, in the present study it is attempted to compare the predicted results of CEL and pure Lagrangian models in the case of AWJM and determine whether this method is applicable for the process or not. Simulation cases based on experimental results are employed and discussion on the predicted cutting zone dimensions, stress and temperature field is conducted.*

Keywords: *Abrasive Waterjet Machining, Finite Element Method, Coupled Eulerian-Lagrangian Formulation.*

1. Introduction

Abrasive Waterjet Machining is one of the most frequently employed non-conventional machining process, along with laser cutting and Electrical Discharge Machining. Compared to the conventional machining processes, such as turning or milling, AWJM has several advantages, as it does not require the utilization of a cutting tool, it is able to process a variety of material types and it is considered as a cold machining process, as it is not associated with the development of heat affected zones in the workpiece [1]. Furthermore, AWJM enables the creation of complex features on workpieces and is regarded as an environmentally friendly process, as it does not produce or employ harmful substances such as lubricants or coolants [1, 2].

During AWJM, material is removed from the workpiece by the impact of a high speed water jet, which contains abrasive particles, on the workpiece surface. As a pure water jet is only able to process soft materials, in AWJM the high-pressure waterjet is mixed with the abrasive particles in a mixing chamber and after the jet is homogenized; the accelerated abrasive particles impact the surface, removing material by erosion. In AWJM, two different mechanisms of material removal can be observed.

More specifically, during ductile erosion, the material undergoes plastic deformation, so micro-machining takes place by removal of microscopic chips, whereas during brittle erosion, crack growth, crack propagation and intersection cause material to be removed, even near the impact zone [1]. The fundamental process parameters of AWJM are the flow rate and pressure of the water jet, the nozzle characteristics, the traverse speed, the stand-off distance, the material type and geometry of abrasive particles, as well as the material of the workpiece [1, 3].

Apart from experimental studies, for the purpose of understanding and optimizing AWJM process, interest on the theoretical study of AWJM, as well as the development of reliable numerical models has begun to grow. After the first theoretical models describing the results of abrasive particle impact on the surface of metallic or ceramic workpieces, such as the works of Finnie [4] or Zeng and Kim [5] were created and validated, there was a need for more detailed simulations, in order to be able to predict the deformation of the workpiece and the material removal mechanisms under various conditions. Thus, FE models were created to simulate the impact of abrasive particles on workpiece surfaces, with the first models, such as the one presented by Hassan and Kosmol [6], including a single abrasive particle. These models were able to determine the correlation between waterjet pressure and depth of cut and depict the time evolution of the depth of cut. Apart from metallic workpieces, the effect of AWJM process on ceramic workpieces was studied firstly by Gudimetla and Yarlaggada [7], who developed a FE model with a single abrasive particle impacting a polycrystalline alumina workpiece. They showed that the model can predict the erosion rate with a sufficient accuracy, compared to theoretical models and it could depict the material removal mechanism in a realistic way. Later, researchers developed more advanced models, taking into consideration multiple abrasive particles. Kumar and Shukla [8] conducted a study on the effect of particles impact angle and velocity during AWJM of titanium alloy specimens with steel abrasive particles. They concluded that crater geometry varied considerably with impact angle and velocity until the 17th impact and then the variation was reduced or eliminated.

As in AWJM fluid-structure interaction takes place, other researchers considered the more accurate modeling of the waterjet as important and modeled it by coupled FE formulations or meshless methods. For example Shahverdi et al. [9] and Wenjun et al. [10] created Arbitrary Lagrangian-Eulerian (ALE) models, by modeling the workpiece by a Lagragrian formulation and the abrasive waterjet with an Eulerian mesh. Accordingly, Jianming et al. [11] and Feng et al. [12] presented models for AWJM process in which the abrasive waterjet was modeled with SPH method and the workpiece with Lagrangian FE formulation. These approaches were particularly useful in order to model the flow of abrasive particles [11], as well as their movement starting from the mixing chamber until their impact on the workpiece surface [12]. Another method, suitable for fluid-structure interactions, which has also been used for machining simulations, is the Coupled Eulerian-Lagrangian method. CEL method involves the use of both Lagrangian and Eulerian regions in the same model and is able to overcome the problems associated with simulations with large deformations, as it does not require element deletion or remeshing technique for material removal. In CEL formulation, material removal is conducted as a continuous flow of material, due to forces occurring from interaction of different bodies or other force fields. Up to now, several works on simulation of machining processes with CEL have been published [13, 14], even on waterjet-assisted machining [15].

In this paper, an investigation on the applicability of CEL formulation in AWJM simulations is attempted. Results from CEL simulations will be compared to those of the more established Lagrangian formulation, in order to determine whether CEL model can achieve high accuracy in the prediction of cutting zone dimensions, stress and temperature fields and also depicts the phenomena occurring during AWJM realistically. For the Lagrangian models, element deletion will be employed, whereas for the CEL model the abrasive particles are formulated as Lagrangian bodies and the workpiece is formulated as Eulerian. After the simulations are carried out, results between CEL and Lagrangian models and compared and discussed.

2. Methodology

In the present work, 3D explicit thermo-mechanical models were created in Abaqus software for both cases. The comparison of the results of Lagrangian and CEL models will be conducted for three different experimental cases from the relevant literature [16]. In the Lagrangian model, both the abrasive particles and the workpiece were modeled using the Lagrangian formulation, whereas in the CEL approach the particles were Lagrangian and the workpiece was Eulerian. In both cases, the particles were modelled with a single C3D8RT mesh element, which had diagonal dimension of 0.2 mm (Grit 80). The workpiece had the same mesh size in both cases (210,120 elements), with a minimum element size of $4x10^{-2}$ mm and a maximum element size of 0.1 mm; mesh type of the workpiece in the Lagrangian formulation was C3D8RT and in the Eulerian formulation EC3D8RT. Finally, dimensions of the workpiece were 6 mm height, 4 mm length and 6 mm width for both cases.

In order to be able to simulate the abrasive particle flow realistically for the various simulation cases, calculations were carried out. Steady abrasive mass flow was divided by particle weight, in order to calculate the abrasive particle quantity per second. Then, the number of particles used within the total simulation time was calculated with a simple division. To calculate the initial position of the particles, it was assumed that they were spaced evenly in the direction of travel, with their distance calculated by multiplying their velocity with the simulation time and dividing with the number of particles in that time. For the horizontal position of the abrasive particles, a Gaussian distribution was assumed, keeping the particles within the nozzle diameter range. The jet impact position was in the middle of the top left edge and the angle was 90^0 in both cases.

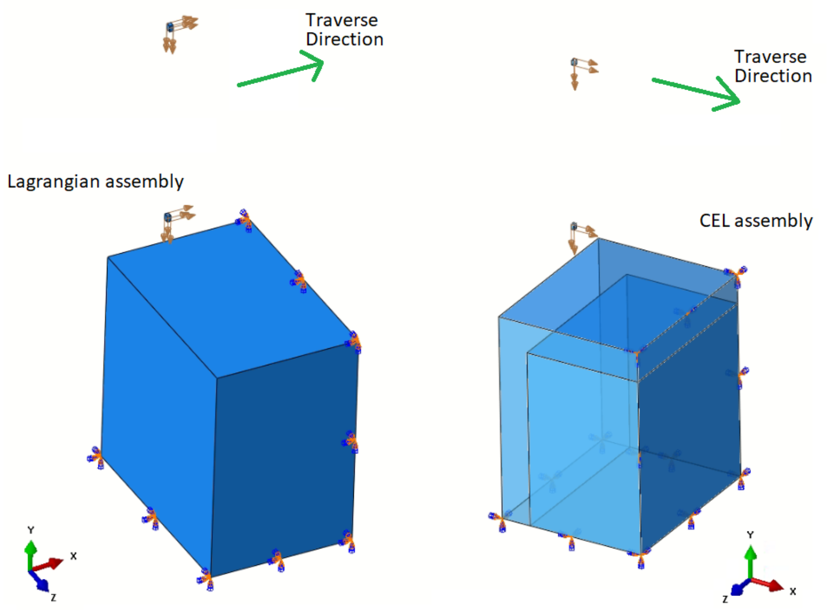

Figure 1 – Model assembly with the two different formulations

In the CEL model, in order to create the Eulerian workpiece, a workpiece Eulerian part and a slightly larger void Eulerian part were created. Then, the workpiece part was placed in the void part, with 1 mm clearance in the jet impact area, to allow for material movement, since any material reaching the boundary would be deleted otherwise. After that, the volume fraction tool in Abaqus was utilized. This tool compares the two instances and creates a scalar discrete field, based on the percentage of occupation of the void instance by the workpiece instance, so then an initial material assignment condition can be created, in order to fill that created space with the workpiece material. In the

Lagrangian formulation, the workpiece was constrained at the bottom and right face. In the Eulerian formulation, material movement was constrained at the bottom and right face as well. Fig. 1 presents the assembly of the two models side by side, including boundary conditions.

To model the workpiece material response to the process, the Johnson-Cook plasticity and damage model was chosen for both cases [17]. Material constants for AISI 1018 steel were adopted from literature [18]. In the Lagrangian model, when an element reaches 100% damage, it is deleted from the simulation. However, there is no element deletion or relevant feature in the CEL formulation workpiece in Abaqus software [19]. The abrasive particle material parameters were adopted from literature as well [20]. In addition to normal parameters, a deletion criterion was adopted, to reduce computation time due to particle movement after collision with the workpiece. When the particle reached a critical stress of 150 MPa, it was deleted from the simulation. Furthermore, coefficient of friction between the particles and the workpiece was considered to be 0.1. Due to high strain rates, adiabatic heating of the workpiece is considered, with a coefficient of 90%, converting that percentage of plastic work to heat [20] and initial model temperature was set to 20^{o}C. An initial vertical velocity was given to each abrasive particle, according to waterjet pressure value in each case, and the same jet traverse speed was applied in all simulations, namely 3.83×10^{-4} m/s. These values were adopted from literature [16] and are presented in Table 1.

Table – Particle Velocities for each simulation case

Simulation case	Pressure (MPa)	Velocity (m/s)
1	100	400
2	200	620
3	350	810

3. Results and discussion

At first, simulation results were compared to experimental ones, in order to assess their validity. The simulation time of 1 ms was sufficient to start the erosion process on models of both formulations. Comparing the predicted cutting forces for models of both formulations to the experimental ones [16], it was verified that the present model simulates the initial stages of abrasive waterjet cutting. In the simulations, cutting forces never exceeded 1N, therefore indicating that the models do indeed fall into the initial cutting stage.

Then, the investigation on the applicability of CEL formulation for AWJM simulations was carried out, based on data from the three different experimental cases. In Fig. 2, resulting dimensions of the cutting zone for all cases and both formulations are presented. In respect to Fig. 1, width direction is in the z axis, traverse direction is in the x axis and depth of cut in the y axis. It is noted that width of cutting zone and cutting zone length along the traverse axis are almost identical for both formulations in most cases. This is justified, as due to the relatively low traverse speed, the main cutting action during the simulation time is towards the depth of cut direction rather than the other two directions.

An obvious difference, though, is that although both models predict correctly the increase of depth of cut with increased abrasive particle speed, the predicted depth of cut is significantly lower in the CEL formulation than in the Lagrangian one. A probable explanation for that outcome is that, as in the CEL formulation no element deletion can be specified, the brittle erosion mechanism, present in experimental works, cannot be properly represented in the simulation. Thus the resulting dimensions of the cutting zone for the CEL formulation are only caused by ductile erosion, especially due to plastic deformation.

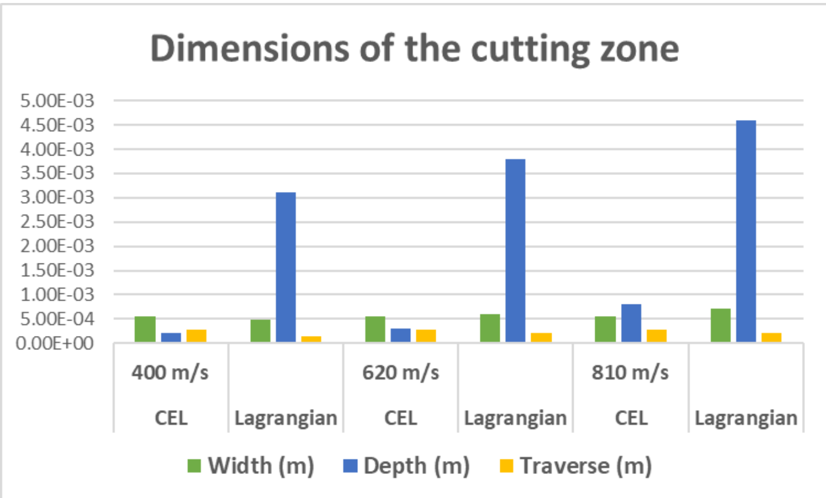

Figure 2 – Dimensions of the cutting zone for all cases for both formulations

In order to further observe the differences between the two types of models, snapshots from several stages of the AWJM process with both models are presented in Fig. 3. In both cases, material removal takes place as expected, caused by the impact of abrasive particles on the surfaces and craters are formed and widened as time progresses. However the shape and dimensions of the cutting zone differ considerably, even from the first stages of the simulations.

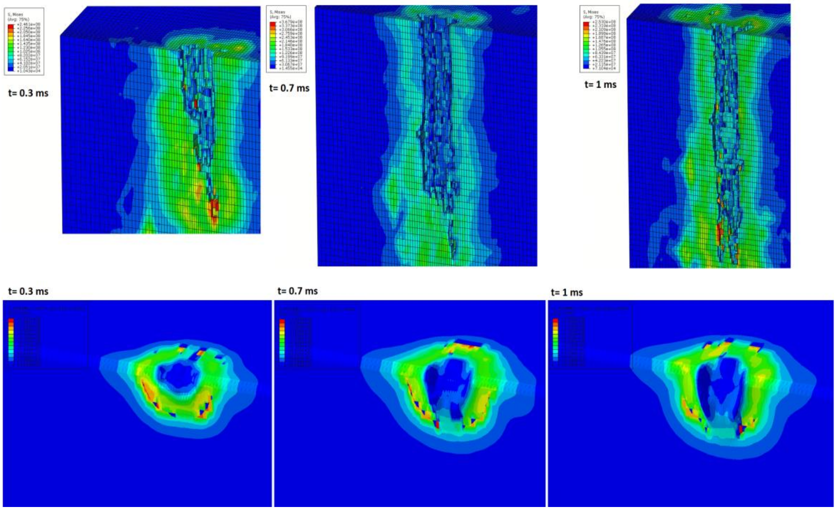

Figure 3 – Comparison of snapshots of the AWJM simulation with Lagrangian (upper row) and CEL models (lower row)

More specifically, in the case of Lagrangian model, the depth of cut is considerably larger in any case and the cutting zone has distinctive erosion marks produced by deleted elements and further erosion of the new surfaces. Although material removal is more evident in the direction of depth of cut, erosion occurs sometimes in lower regions perhaps due to the intense stress propagation as well as in regions near the main cutting zones, perhaps due to reflected abrasive particles. Nevertheless, in the case of CEL model, it seems that the workpiece material is only compressed due to the particle impacts and the deformation of the workpiece is considerably smaller and more uniform, with an initial crater being widened towards the depth of cut and traverse direction and with an almost symmetrical stress field developing away from the main cutting zone. Thus, in conjunction with the results presented in Fig. 2, it becomes clear that CEL models can account for only the plastic deformation due to particle impacts and propagation of erosion cannot be represented.

After the differences between the CEL and Lagrangian formulation models regarding the predicted dimensions of cutting zone and material removal mechanisms were discussed, the differences regarding the prediction of stress and temperature distribution by the two different formulations are also discussed afterwards. Fig.4 presents the von Mises stress distribution comparison for the CEL formulation on the left and the Lagrangian one on the right. In the figure concerning CEL, plastic deformation zone is visible at the center of the top edge. Stresses are concentrated around that area, as for the Lagrangian model, depicted on the right figure. However, the previously mentioned brittle erosion mechanism is missing in the CEL model results. Thus no material removal is noticed around the deformed area, in contrast to the Lagrangian model results, where elements around the impact zone have been deleted and the evolution of the erosion process is visible near the edges. Furthermore, stress values are slightly lower for the CEL model; for example in Fig.4 maximum stress value in the cutting zone is 209.8 MPa, whereas for the Lagrangian is 253 MPa.

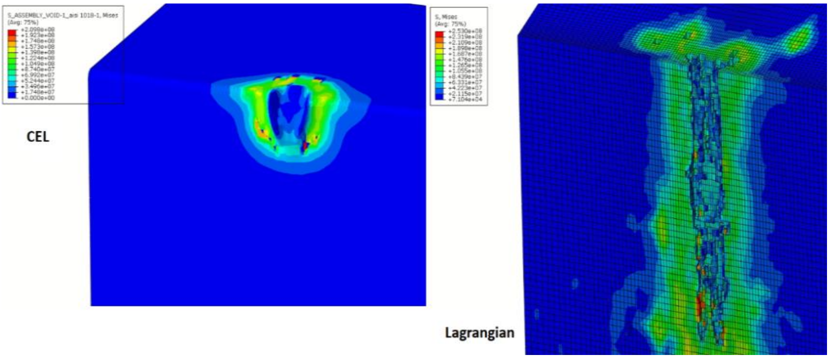

Figure 4 – Comparison of the cutting zone morphology for the CEL (left) and the Lagrangian (right) formulations of the workpiece for the 810 m/s abrasive velocity case and Von Mises stress distributions

Regarding temperature distribution, Fig. 5 presents the maximum predicted temperature in all cases. Since 90% of plastic work is converted to heat, temperatures in all CEL formulations are almost identical, with only 2^{o}C difference per case and 4^{o}C maximum change. Temperatures of the Lagrangian models on the other hand increase almost 20^{o}C from the lowest velocity to the highest velocity. A probable explanation for this is that, after an element is deleted, nearby elements gain more free degrees of movement, so their plastic deformation is higher compared to the constrained CEL ones, something that results in higher temperature increase as well. Furthermore, in higher abrasive velocities cases, elements deform more and thus the difference of the predictions of the two methods becomes higher. Finally, it is worth mentioning that all predicted temperatures from the simulations are in compliance with experimental literature results for the same material [21].

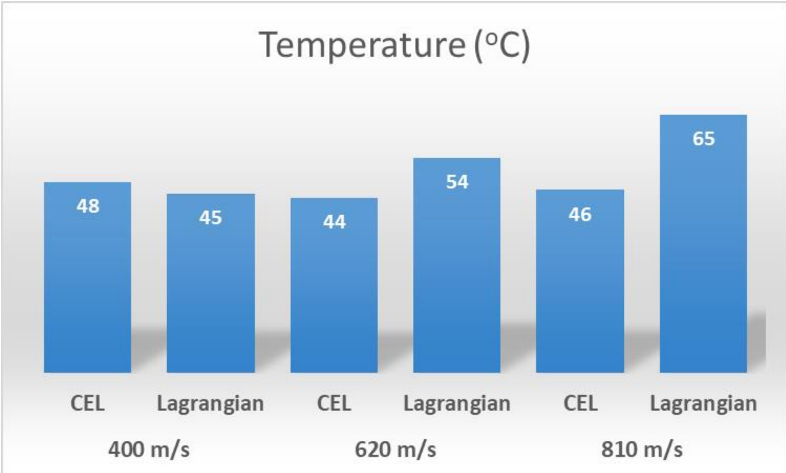

Figure 5 – Maximum temperature results for all cases

By taking into account all the previous comparisons between the CEL and Lagrangian formulation models, it becomes obvious that the Lagrangian model is more appropriate for the simulation of AWJM and especially material removal process from the workpiece. Although it had been proven that CEL formulation is superior to the Lagrangian one for cases with high plastic deformation, it was shown that the underestimation of the dominant erosion phenomenon during AWJM finally results in a significant underestimation of the depth of cut as well as workpiece temperature. The contribution of the present study can be regarded as important as, to the authors' knowledge, no study on AWJM with CEL formulation has been yet presented and definitely no comparison of its results with results of Lagrangian models has been yet conducted in the relevant literature.

4. Conclusions

In the present paper an investigation regarding the applicability of CEL approach in AWJM simulations was carried out. CEL and Lagrangian simulation models were developed based on experimental data and comparison between them were conducted, in respect to prediction of cutting zone dimensions, stress and temperature distributions and accuracy of representation of material removal mechanisms. Based on the simulation results various conclusions were drawn.

The simulation results indicated that Lagrangian model is more adequate than CEL, regarding depth of cut prediction in AWJM process. Although material removal after the impact of abrasive particles occurred from the initial stages, as with the Lagrangian model and the trend of increase of depth of cut with increasing pressure was captured, only the plastic deformation mechanism was able to be observed with CEL, whereas the erosion and its propagation in the workpiece material was not simulated. Furthermore, comparison with results from the Lagrangian model showed that depth of cut was significantly underestimated while width and traverse length were similar between the two types of models. Finally, relatively lower stress values were observed in the CEL model and temperature variation was minimal as the additional plastic deformation occurring in the newly created surfaces of the cutting zone due to erosion was not calculated. In conclusion, although CEL has been proven sufficient for machining simulations it is deduced that it not as successful in simulating material removal due to erosion as it occurs in AWJM.

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ДОСЛІДЖЕННЯ ЗАСТОСОВНОСТІ РІВНЯННЯ ЕЙЛЕРА-ЛАГРАНЖА ПРИ МОДЕЛЮВАННІ АБРАЗИВНОЇ ВОДОСТРУМЕНЕВОЇ ОБРОБКИ

Анотація. *Нетрадиційні процеси обробки розглядаються як надійні альтернативи загальноприйнятим традиційним способам обробки важкооброблюваних матеріалів. Зокрема, для цієї мети вигідна абразивна водоструменева обробка (AWJM), оскільки цим методом можна обробляти широкий спектр матеріалів заготовки і не викликати зон термічного впливу. Для вивчення явищ, що відбуваються під час AWJM, слід проводити чисельне моделювання поряд з експериментами. Оскільки процеси обробки пов'язані зі значною лагранжевими (CEL) кінцевими елементами (FE) виявилися значно більш точними для цієї деформацією матеріалу, моделі з сполученими ейлерово- мети в порівнянні з чисто лагранжевськими моделями. Однак очевидна відмінність полягає в тому, що хоча обидві моделі правильно передбачають збільшення глибини різання при збільшенні швидкості абразивних частинок, передбачена глибина різання в середовищі CEL значно нижче, ніж в лагранжевській. Можливим поясненням цього результату може бути те, що, оскільки в формулюванні CEL не може бути зазначено видалення елемента, механізм крихкої ерозії, який присутній в експериментальних роботах, не може бути належним чином представлений в моделюванні. Таким чином, результуючі розміри зони різання для моделі CEL обумовлені тільки пластичною ерозією, особливо через пластичну деформацію. У разі моделі Лагранжа, глибина різання в будь-якому випадку значно більше, і зона різання має характерні сліди ерозії, викликані видаленими елементами, і подальшу ерозію нових поверхонь. Проте, в разі моделі CEL, здається, що матеріал заготовки стискається тільки через удари частинок, і деформація заготовки значно менша і більш однорідна, при цьому початковий кратер розширюється в напрямку глибини різання і поперечного напрямку. і з майже симетричним полем напружень, що розвиваються далеко від основної зони різання.Таким чином, в цьому дослідженні зроблено спробу порівняти передбачені результати моделей CEL і чисто лагранжевських в разі AWJM і визначити, чи може бути застосований цей метод для процесу чи ні. Використовуються випадки моделювання, засновані на експериментальних результатах, і проводиться обговорення прогнозованих розмірів зони різання, полів напружень і температури.*

Ключові слова: *гідроабразивна обробка; метод кінцевих елементів; рівняння Ейлера-Лагранжа; глибина різання; композиція; ерозія матеріалу; напруження.*