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# ABRASIVE WATER JET PIERCING SIMULATION OF CARBON FIBRE REINFORCED POLYMER

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***Abstract:*** *The paper presents the piercing simulation of a composite material (CFRP), using abrasive water jet (AWJ). AWJ cutting process is a well-known technique applied for trimming the outer contour of CFRP parts with complex shapes. The challenge of CFRP processing is to machine geometries, such as internal shapes, holes, or slots, where the material needs to be pierced with AWJ. In this case, the AWJ strikes the composite material with a very high energy, introducing delamination on the material. To analysis the AWJ piercing, a theoretical simulation was carried out using Finite Element Analysis (FEA). The purpose of this dynamic analyzes performed is to study the stresses and deformations that appears in the material during the process.*

***Key words:*** *abrasive water jet cutting, water jet piercing, simulation, von Mises stress CFRP, composite materials, FEA*

## 1. INTRODUCTION

In recent decades, composite materials, especially Carbon Fibre Reinforced Polymer (CFRP), are increasingly integrated in high-end industries such as automotive or aerospace, but also in the construction of goods consumer [1, 2]. The main distinguishing properties of CFRP are high mechanical properties and low weight [2]. Abrasive water jet (AWJ) technologies are suitable for machining composite materials such as CFRP [2-4]. The main AWJ technologies for CFRP processing are cutting and drilling and less commonly are milling and turning [1–3]. This processing technology is using a high-pressure water jet mixed with abrasive grains [2], as shown in figure 1. The water is pressurized at 300-600 MPa using a high-pressure pump and the abrasive grains are added to the jet due to venturi phenomenon. The main application of AWJ cutting in the case of machining composite materials, is to cut the contour of the part, also called trimming. When an outer contour is cut, the AWJ starts the process from the outside of the CFRP workpiece and the AWJ does not hit the material when the jet starts. The problem appears when an internal contour, hole or slot needs to be machined. In this case, the AWJ hits the composite material with a very high energy during the piercing process [4]. This phenomenon can generate delamination of the composite material, as shown in figure 1 [4–6].

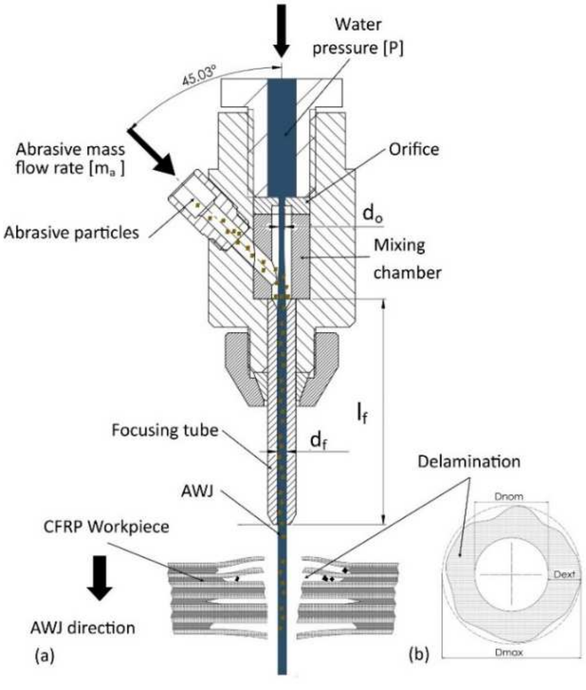

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**Fig. 1.** The abrasive water jet piercing of CFRP [2]

Shanmugam et al. during the investigations carried out on the piercing of the composite materials, observed that the material delamination takes place because of the shock wave generated during the impact [7]. Decreasing the energy with which the jet hits the composite material (decreasing the pressure) the delamination of the material can be reduced [2, 4]. Pre-drilling a starter hole is a solution to avoid the impacting of the CFRP with AWJ. This pre-drilling is an extra operation which introduces extra costs and machining time [5].

For the analysis of the phenomena that occur during the impact between the composite material and the high-pressure AWJ, a simulation was carried out using Finite Element Analysis (FEA). The simulation was caried on using ANSYS software.

## 3. FEA SETUP

The first step of the simulation was to calculate the AWJ velocity, when the jet hits the composite material. Bernoulli's equation is used to determine this speed. Based on the water jet pressure, the velocity with which the fluid exits the focusing tube is obtained. The process parameters used in simulation are selected from Omax water jet cutting system. The values for water jet velocity m/s ($V_{jet}$) varies between 100 and 350 m/s. Thus, the parameters used are plotted in Table 1.

*Table 1*

**The process parameters**

| **Parameters** | **Values** |
|---|---|
| Water jet velocity, m/s ($V_{jet}$) | 100, 150, 200, 250 ,300, 350 |
| Stand-off distance, mm | 0.2 |
| Focusing tube diameter, mm | 1.02 |

By approximating the velocity of the abrasive grains as being the same as the velocity of AWJ, the water jet was assimilated with a sphere moving with a certain speed that hits the composite material. The size of the sphere is equal to the inner size of the focusing tube (1.02 mm). Considering that on the distance between the cutting head and the material to be processed (0.2 mm) the jet keeps its shape. The jet characteristics used in this FEA simulation is a non-deformable ball.

The material used is a composite material reinforced with carbon fibers and its characteristics are presented in Table 2.

*Table 2*

**Properties of the material used.**

| **Material** | **Tensile modulus [Pa]** |
|---|---|
| CFRP | Direction X 1.21E+11<br>Direction Y 8.6E+09<br>Direction Z 8.6E+09 |
| **Poisson ratio** | **Material density [kg·m–3]** |
| XY - 0.27<br>YZ - 0.4<br>XZ - 0.27 | 1490 |

ANSYS software and Explicit Dynamics module was used for analyzing the impact between AWJ and composite material. The interface of the ANSYS software is shown in figure 2.

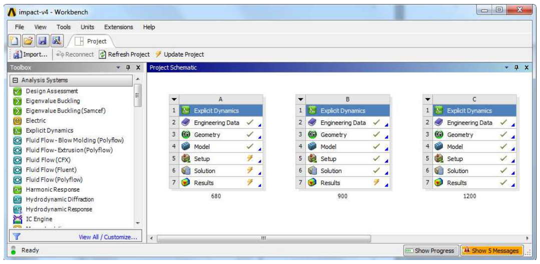


**Fig. 2.** ANSYS FEA software interface, "Explicit Dynamics" module

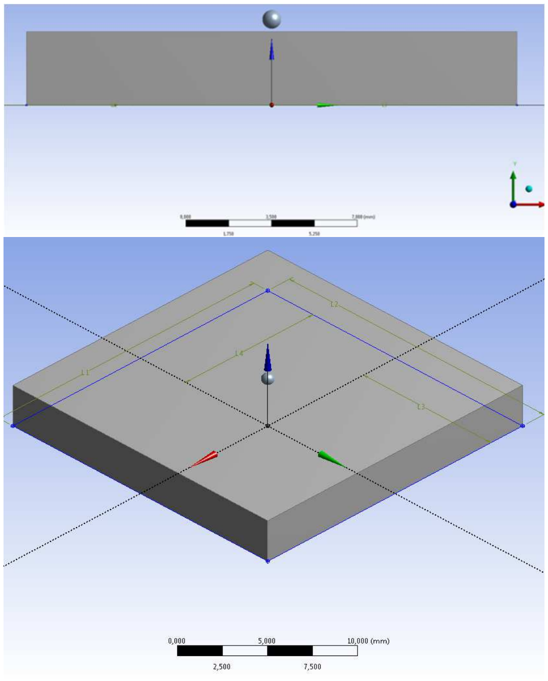


**Fig. 3.** The 3D parts of the components

The CFRP workpiece dimensions used in the simulation are 20 x 20 x 3 mm, as illustrated in figure 3.

For discretization of the geometric model, from the ANSYS library, the Solid45 finite element was selected. Both automatic and manual discretization were used. Figure 4 shows the discretized model.

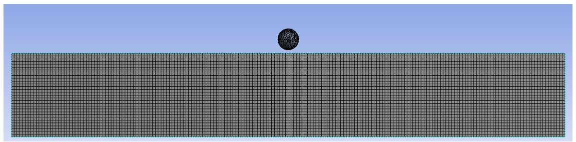


**Fig. 4.** Discretization of the geometric model

## 3. RESULTS AND DISCUSSIONS

The aim of present dynamic analysis was to determine the stresses and deformations that appear in the material. The impact between the high velocity water jet and the composite material was investigated. In the case of stresses, it was chosen to present the stresses calculated according to the von Mises yield criterion. The main observation noticed during the dynamic analysis can be structured in 3 cases where the water jet velocity was raging from 100 m/s up to 250 m/s.

***Case 1 water jet velocity $V_{jet}$ =100 m/s:***

- For a jet velocity of $V_{jet}$ 100 m/s, the jet penetrated the material in a percentage of 60%.
- The resulting maximum von Mises equivalent stress has a value of 133 MPa.
- The maximum elastic deformation is 0.052 mm.

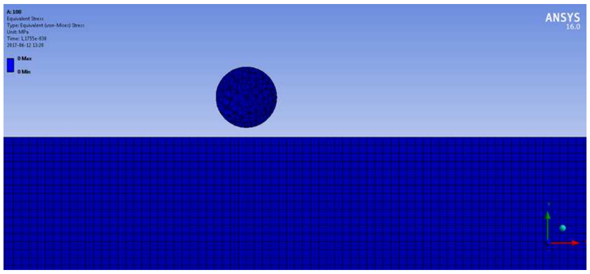
***Case 2 water jet velocity $V_{jet}$ =200 m/s:***

- For a jet velocity of $V_{jet}$ 200 m/s, the jet penetrated the material in a percentage of 90%.
- The resulting maximum equivalent von Mises stress is 180 MPa.
- The maximum elastic deformation is 0.0546 mm.

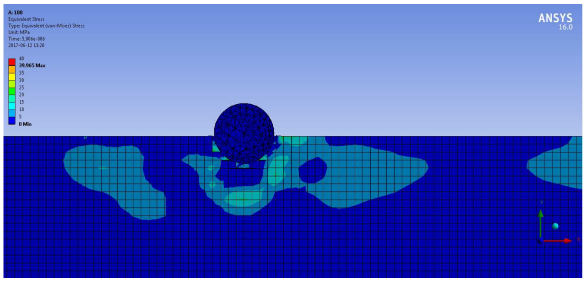
***Case 3 water jet velocity $V_{jet}$ =250 m/s:***

- At a jet speed of $V_{jet}$ 250 m/s, material penetration was observed throughout the thickness.
- The resulting maximum von Mises equivalent stress has a value of 311 MPa.
- The maximum elastic deformation is 0.0539 mm.

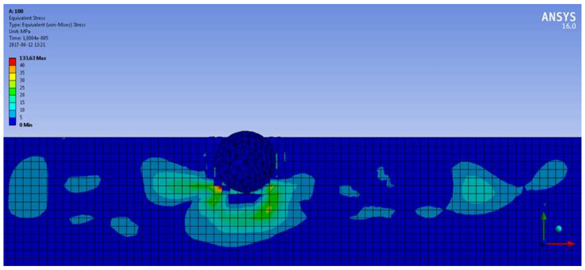
The distribution and evolution of the von Mises equivalent stress $\sigma_{ech}$ (MPa) for different AWJ speeds $V_{jet}$ (100, 200 and 250 m/s) are illustrated in figure 5.



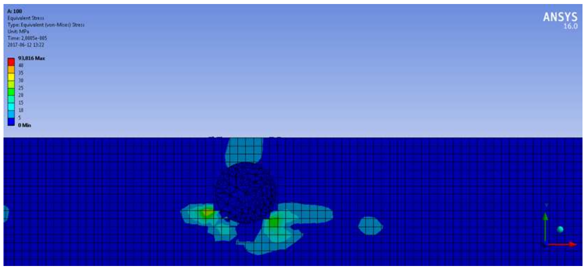
**$V_{jet}$ 100 m/s,** Time 0 s, Von Mises Stress $\sigma_{ech}$ 0 MPa



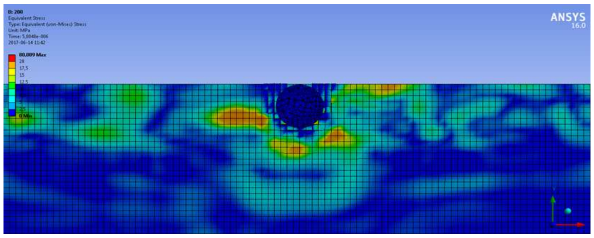
**$V_{jet}$ 100 m/s,** Time 5e-006 s, Von Mises Stress $\sigma_{ech}$ 39.96 MPa



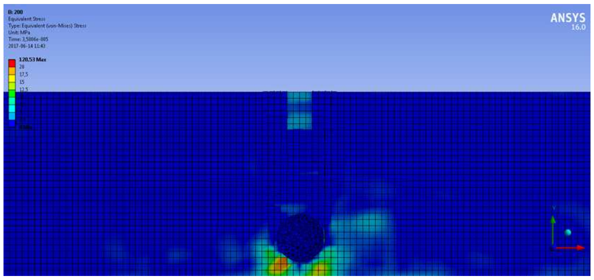
**$V_{jet}$ 100 m/s,** Time 1e-005 s, Von Mises Stress $\sigma_{ech}$ 133.63 MPa



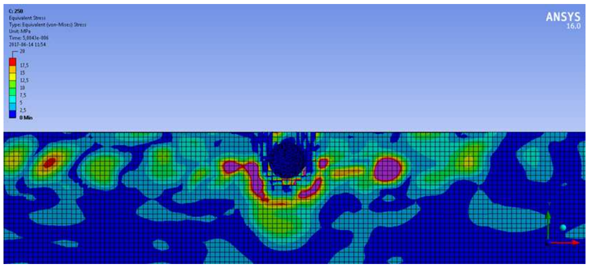
**$V_{jet}$ 100 m/s,** Timp 2e-005 s, Von Mises Stress $\sigma_{ech}$ 93.81 MPa



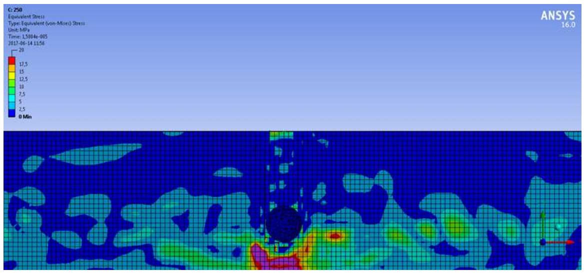
**V$_{jet}$ 200 m/s,** Time 5e-006 s, Von Mises Stress $\sigma_{ech}$ 180 MPa



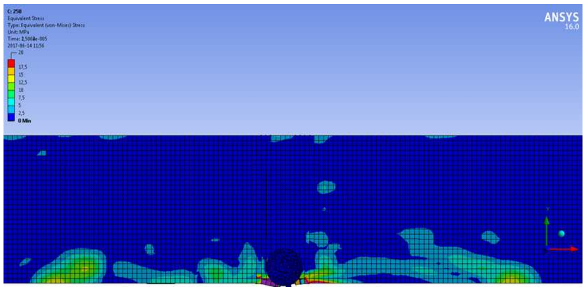
**V$_{jet}$ 200 m/s,** Time 3.5e-005 s, Von Mises Stress $\sigma_{ech}$ 120 MPa



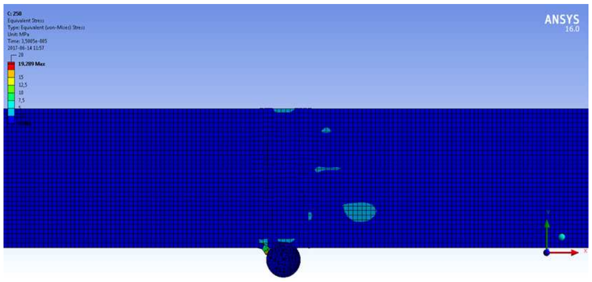
**V$_{jet}$ 250 m/s,** Time 5e-006 s, Von Mises Stress $\sigma_{ech}$ 72.98 MPa



**V$_{jet}$ 250 m/s,** Time 1.5e-005 s, Von Mises Stress $\sigma_{ech}$ 50.99 MPa



**V$_{jet}$ 250 m/s,** Time 2.5e-005 s, Von Mises Stress $\sigma_{ech}$ 311.54 MPa



**V$_{jet}$ 250 m/s** Time:3.5e-005 s, Von Mises Stress $\sigma_{ech}$ 19.28 MPa

**Fig. 5.** The distribution and evolution of the von Mises stress $\sigma_{ech}$ (Mpa)

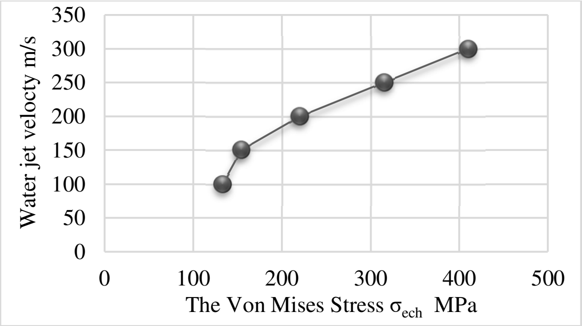
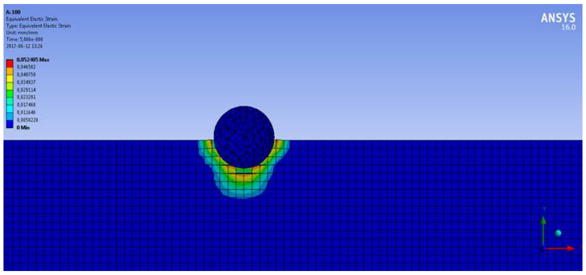


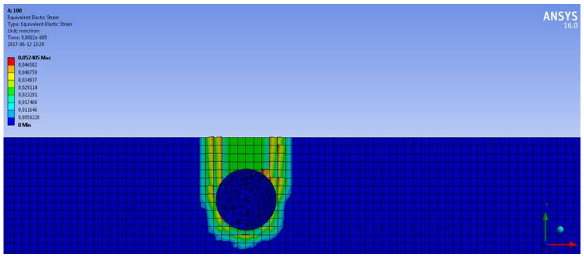
**Fig. 6.** Effect of AWJ velocity on von Mises stress ($\sigma_{ech}$)

As illustrated in figure 6, as the AWJ velocity increases from 100 to 300 m/s, the resulting the von Mises equivalent stress increases from 130 to 410 MPa.

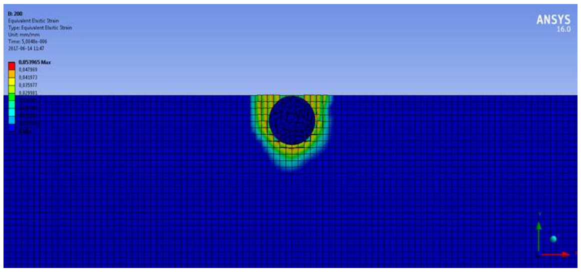
The figure 7 presents the distribution and evolution of the elastic deformations for different velocities of the water jet V$_{jet}$ (100, 200, and 250 m/s).



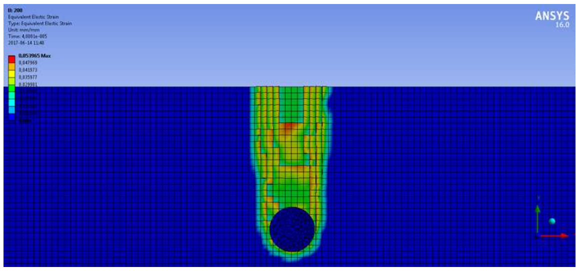
**V$_{jet}$ 100 m/s,** Time 5e-006 s, Deformation 0.052 mm



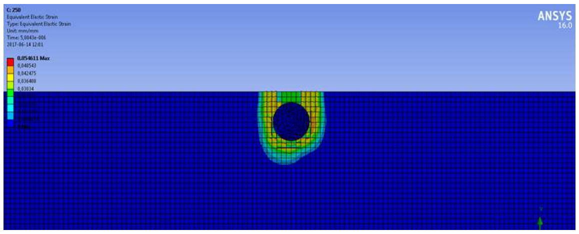
**V$_{jet}$ 100 m/s,** Time 9e-005 s, Deformation 0.052 mm



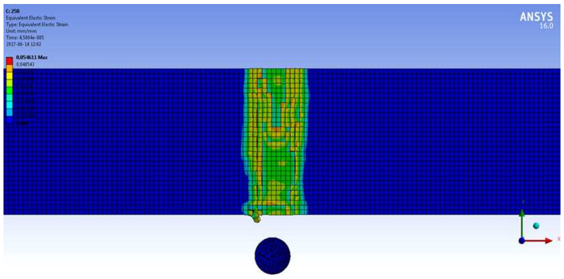
**$V_{jet}$ 200 m/s,** Time 5e-006 s, Deformation 0.0539 mm



**$V_{jet}$ 200 m/s,** Time 4e-005 s, Deformation 0.0539 mm



**$V_{jet}$ 250 m/s,** Time 5e-006 s, Deformation 0.0546 mm



**$V_{jet}$ 250 m/s,** Time 4.5e-005 s, Deformation 0.0546 mm

**Fig. 7.** The distribution and evolution of the elastic deformations

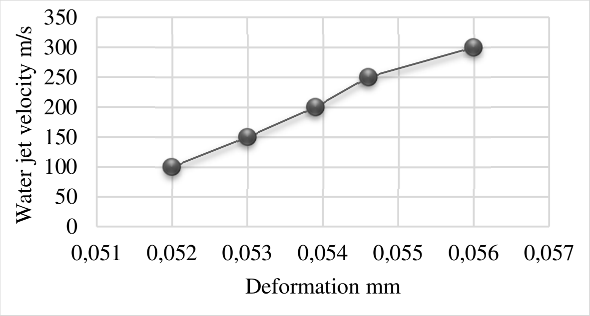


**Fig. 8.** Effect of AWJ velocity on material deformation

In the case of elastic deformations that appeared in the CFRP material during the piercing, it can be observed, that increasing the AWJ velocity from 100 to 300 m/s, the deformations increase between 0.052 and 0.056 mm (figure 8).

## 4. CONCLUSION

The main challenge on machining CFRP with AWJ is piercing the material without delamination. Material delamination is introduced during the shockwave generated by the AWJ hitting the material. The paper presents the piercing simulation using Finite Element Analysis. The purpose of this dynamic analyzes performed was to study the stresses and deformations that appears in composite during the process. The main observations are:

- Increasing the abrasive water jet velocity, the von Mises equivalent stress increases up to 410 MPa. To decrease delamination, it is recommended to decrease the AWJ pressure, decreasing the von Mises stress introduced into the material.
- In the case of the elastic deformations that appeared during the piercing, it can be seen, that by increasing the AWJ pressure, the deformations increase up to 0.056 mm. Elastic deformations of the material can break the polymer matrix, thus causing delamination.

## 5. ACKNOWLEDGEMENT

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## Simularea procesului de găurire cu jet de apă și abraziv a materialelor compozite armate cu fibră de carbon

**Rezumat:** Lucrarea prezintă simularea procesului de găurire a materialului compozit, CFRP, cu jet de apă și agent abraziv. Tăierea cu jet de apă și agent abraziv (AWJ) este o tehnologie bine-cunoscută utilizată pentru tăierea conturului exterior al pieselor din CFRP cu forme complexe. Provocarea prelucrării materialului CFRP este de a prelucra geometrii cu contururi interne sau găuri, unde materialul trebuie să fie perforat cu AWJ. În acest caz, AWJ lovește materialul compozit cu o energie foarte mare, introducând fenomenul de delaminare a materialului. Pentru analiza procesului de găurire cu AWJ, a fost efectuată o simulare utilizând analiza cu elemente finite (FEA). Scopul acestei analize dinamice efectuate este de a studia tensiunile și deformațiile care apar în material în timpul procesului.

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