Comparison of FEM software for 2D heat transfer analysis in sheet metal laser cutting

Daniel Mejia [1,2], Aitor Moreno [2], Iñigo Barandiaran [2], Óscar Ruíz [1]

(1) : CAD/CAM/CAE Laboratory, Universidad EAFIT, K49 # 7 Sur – 50, Medellín (Colombia)
+[57] 4 261 9500 9521
{dmejiap, oruiz}@eafit.edu.co

(2) : Vicomtech-IK4, Mikeletegi Pasealekua, 57, Donostia - San Sebastián (Spain)
+[34] 943 30 92 30
{dmejia, amoreno, ibarandiaran}@vicomtech.org

Short Abstract: Finite Element Methods (FEM) have been used to simulate a variety of physical phenomena in the industrial manufacturing sector. This paper addresses the simulation of the thermal properties in the metal sheet laser cutting. A comparison of very well known FEM software is presented. The results show the differences obtained and the stability of the mesh resolution.

Key words: Industry 4.0, Finite Element Methods, Simulation, Heat Transfer

1- Introduction

Historically, the simulation techniques have been used to simulate all kind of physical behaviour: structural deformations, stress calculation, fluids simulation, electromagnetic fields have benefit from the Finite Element Methods (FEM). The industrial impact of such techniques is very broad, and particularly in the design of machining processes as they have a very relevant role to get high quality products.

In the last years, the manufacturing landscape is adopting the novel concepts presented under the Industry 4.0 tag [PT1]. The technologies behind the Industry 4.0 concept allow manufacturers to introduce novel technologies and new relationships across the whole product life cycle: from the very early design stages, the production and the quality control till the recycling. The information flux is not linear anymore, and the feedback comprehension and reutilisation in earlier stages of the production line will enable continuous improvement and optimization of the processes.

Simulation techniques are part of the new proposed technological framework [PT1]. In the manufacturing scenarios, the simulation of the machining processes provides measurable benefits for the manufacturing industries, e. g, less wasted resources and energy and enhanced workers' safety.

This paper addresses the simulation of the thermal properties in the metal sheet laser cutting. This machining process uses high power laser to melt the metal sheet and to produce the designed part. The heat propagation has to be consider since a bad programming or configuration of the laser power could damage the metal sheet and therefore and the produced parts would be rejected.

A selection of well known FEM software is presented in Section 2. They are compared to obtain the differences and stability of the thermal simulation when some parameters of the experiment vary. Section 3 presents the details of the experiment and Section 4 address the obtained results and the discussion. Finally, the paper presents the conclusions and the future work.

2- Related Work

Continuum mechanics is the most popular approach to structural and thermal analysis in industrial applications. Simulation of laser cutting processes via FEM analysis has been already addressed by several authors where the 3D model of the piece is discretized and then a PDE solution is approximated with an adequate selection of boundary conditions which model the laser beam and the heat loss by air convection [JK1][TL1][YA1].

Currently there is a vast variety of available software for FEM analysis. However, in our literature review the thermal (and stress) analysis of the laser machining problem is limited to implementations in commercial FEM software such as Abaqus [YA1], ANSYS [JK1] or MSC Marc [TL1].

3- Design and objective of the experiment

As it was stated in the previous sections, the sheet metal laser cutting is essentially a heat transfer problem. The heat produced by the laser on the sheet surface is high enough to melt the sheet, generating a transversal cut in it. There are lot of variables involved in the success of a machining process.

On one side, the sheet metal properties of the material and its geometry have to be taking into account. On the other side, choosing the right laser emission parameters is essential to produce a good result in the cutting process.

Even if the laser beam is perfectly focused in the target point on the sheet, the generated heat spreads out along the surface of the sheet, modifying temporally its local thermodynamic and physical properties. If the power if too high, the heat might spread too far from the laser spot and damage other regions in the sheet that will be used later to machine parts. These parts might get discarded and therefore, an economical loss in terms of machine time and wasted resources will be accounted.

The introduction of simulation techniques help to determine if a combination of metal sheet and laser power can produce valid parts given a NC machining process.

The proposed experiment will try to simulate a very basic sheet metal machining process with different FEM software and compare the output. The comparison will be in terms of qualitative difference of the simulations and the simulation time required calculating the output.

The next subsections introduce the experiment characteristics, variables and constants. The next section presents the results and a brief discussion about them.

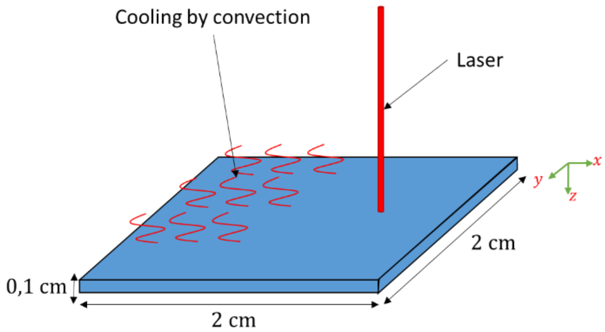

Figure 1: Scheme of laser cutting for metal sheet cutting.

4.1 – Sheet metal laser cutting abstraction

The metal sheet is defined as a flat and homogeneous piece with dimensions$20 \times 20 \times 1$ mm. Cutting by laser machining induces some heat input to the sheet due to the laser discharge perpendicular to the sheet, as well as some heat output due to air convection as illustrated in Figure 1. Thermal equilibrium inside the sheet can be modelled by the following Partial Differential Equation [DH1]:

$$\rho c_p \frac{\partial(u)}{\partial t} = \nabla \cdot (k \nabla u) + \rho c_p (\vec{v} \cdot \nabla u) + S, \qquad (1)$$

where u is the temperature at a point inside the sheet, t denotes the simulation time, ρ is the density, c_p is the heat capacity, k is the thermal conductivity, S is the power density of the laser and $\vec{v}$ is the instant speed of the laser. For the simulations, an alumina sheet is considered with the same physical properties from [YA1]. However, such properties are considered temperature-independent and melting or material removal is not considered for simplification purposes. Ambient temperature is taken as $293\,K$ and the air convection coefficient is taken as $20\ \mathrm{W/m^2K}$. A Gaussian distribution is used to model the laser beam as in [YA1], with a power of 3500 W and a spot radius of 0.1 mm.

4.2 – Case studies

Two case studies have been defined to compare the performance and results of the selected software. The first one just uses a static laser, always aiming to the same point of the metal sheet (see Figure 2). The purpose of this case study is to compare the basic heat transfer capabilities of the FEM software without adding the movement variable.

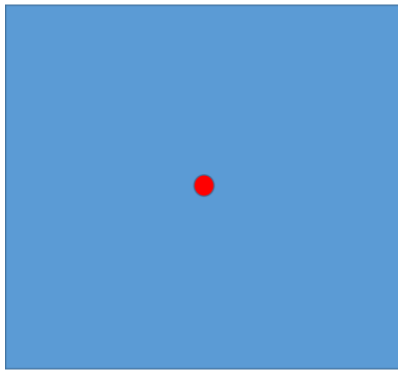

Figure 2: The laser spot is static in the first use case

The second use case shows a moving laser following a counterclockwise circular path (radius of 5 mm) at constant speed of 0.1 m/s (Figure 3). This use case will show the differences between the FEM sofware when the laser is moving. The circular path has been chosen mainly because linear trajectories have been widely studied in the literature as in [JK1,TL1], and in manufacturing applications the cutting trajectory is usually nonlinear.

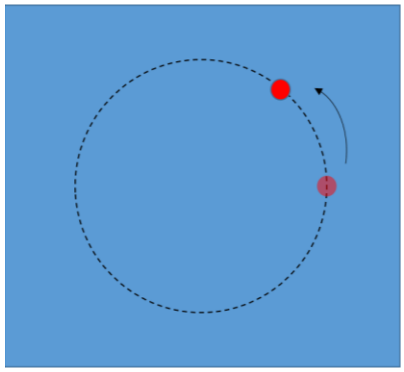

Figure 3: Circular path used in the second use case

4.3 – Geometry discretization

Eq. (1) can be solved numerically by a discretization of the 3D domain. In addition, a 2D simplification can produce accurate results if the heat transfer through the thickness of the sheet is negligible. The simulation is carried in the 2D context by assuming that the laser power does not change along the sheet thickness. In addition, since in real-time applications the trajectory of the laser beam is unknown, a uniform grid of squares is used to discretize the sheet where each element gives a spatial resolution of 0.02 mm in each axis (resolution required to capture accurately the laser heating effects as per Figure 4).

4.4 – FEM Software

The used software for the comparison is:
- FreeFem++ v 3.40-2 for Windows 64-bit.
- FEniCS v 1.0.0 for Windows 32-bits.
- MOOSE for Linux 64-bits running on a VMWare virtual machine.
- Abaqus 6.14-1 and Intel Compiler 16.0 on Visual Studio 2013 for Windows 64-bits.

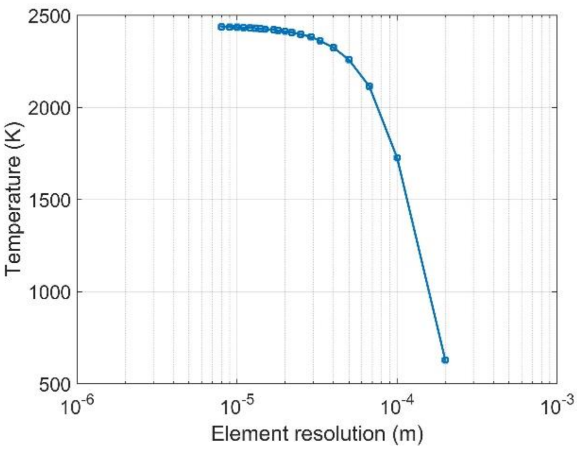

Figure 4: Mesh sensitivity analysis for the static laser source. The temperature is computed at the sheet center at $t = 7 \times 10^{-5}$ s.

5- Results and discussion

Figure 5 presents the relative error of the temperature at the sheet center with respect to MOOSE results for the static case. FreeFem++ coincides the most with the results while Abaqus presents an error around 2%. These errors arise due to many factors such as domain and time integration schemes and numerical solvers.

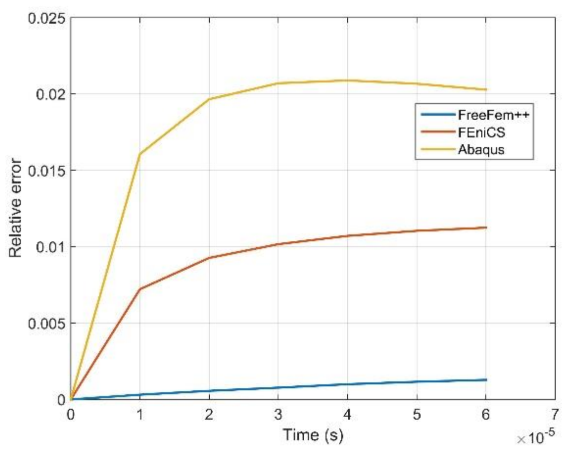

Figure 5: Relative error of the temperature at the sheet center with respect to MOOSE results for the static laser case.

Figure 6 presents the MOOSE temperature distribution of the upper right section of the sheet after 0.05 seconds of simulation time for the moving laser case. Due to the assumptions discussed in section 4.1, the sheet reaches temperatures of 2×10^4 K.

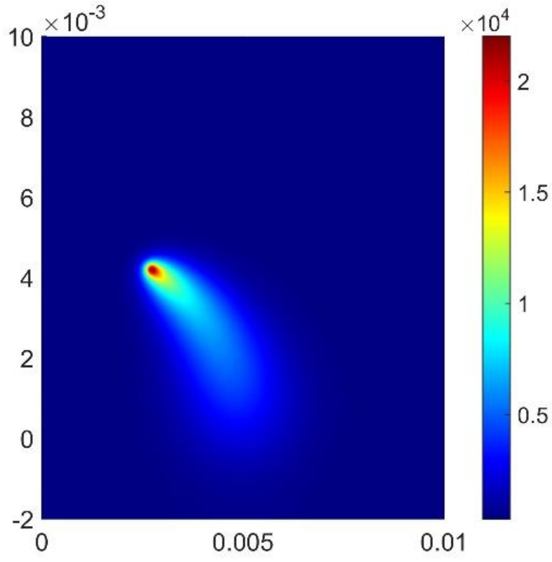

Figure 6: MOOSE temperature distribution at $t = 0.05$ s (moving laser case).

Figure 7 presents the temperature relative error for the Abaqus results with respect to MOOSE results. At a given timestamp ($t = 0.05$ s in the figure), the measured error peaks around the laser path with a maximum value of 14% at the laser spot location. FreeFem++ and FEniCS simulation results presented a maximum relative error of 0.2% and 0.5% respectively. The figures for such results are omitted since they are relatively non-significant compared to Figure 7.

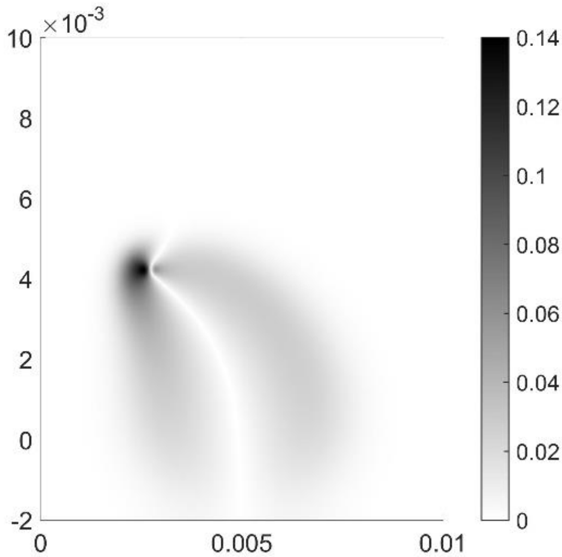

Figure 7: Abaqus vs. MOOSE relative error distribution at $t = 0.05$ s for the moving laser.

5- Conclusions and future work

Comparisons of the results between the chosen FEM software (FreeFem++, FEniCS, MOOSE and Abaqus) showed differences in the temperature distribution of the sheet after laser heating. Such differences are more remarkable between Abaqus and the other FEM software (Figure 7). These differences may appear due to different software parameters such as solvers and integration schemes.

The sensitivity analysis (Figure 4) also shows that mesh resolution is critical for accurate results due to the high frequency nature of the laser beam. Therefore, discretization of real world sheet metals would result in computationally unsolvable systems even under parallelization frameworks such as MPI or GPU computing. Dynamic multi-resolution techniques [ZP1] seem promising since in laser machining, the heat transfer is mainly localized at the laser spot location allowing high mesh resolution in such area and low mesh resolution elsewhere.

As Figure 6 shows, the assumption of physical properties independent from temperature does not represent accurately the physical phenomena. Therefore, the simulation should take into account nonlinear behaviours due to these property changes. The nonlinear effects also affect the stability of the algorithm in terms of the mesh and time resolution. However, this is left as future work.

6- References

[DH1] Dahotre, N. B., Harimkar, S. Laser Fabrication and Machining of Materials. Springer-Verlag US, 2008.

[JK1] Joshi, A., Kansara, N., Das, S., Kuppan, P., Venkatesan, K. A Study of Temperature Distribution for Laser Assisted Machining of Ti-6AI-4 V Alloy. In 12th Global Congress on Manufacturing and Management (GCCM), 97, 1466-1473, 2014.

[PT1] Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D., De Amicis, R., Pinto, E.B., Eisert, P., Dollner, J., Vallarino, I.: Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet. In Computer Graphics and Applications, IEEE, 35(2): 26-40, 2015.

[TL1] Tagliaferri, F., Leopardi, G., Semmler, U., Kuhl, M., Palumbo, B.: Study of the Influences of Laser Parameters on Laser Assisted Machining Processes. In 14th CIRP Conference on Modeling of Machining Operations (CIRP - CMMO), 8, 170-175, 2013.

[YA1] Yilbas, B. S., Akhtar, S. S., Karatas, C. Laser straight cutting of alumina tiles: thermal stress analysis. In The International Journal of Advanced Manufacturing Technology. 58(9), 1019-1030, 2012.

[ZP1] Zeng, K., Pal, D., Patil, N., Stucker, B. A New Dynamic Mesh Method Applied to the Simulation of Selective Laser Melting. In Proceedings of the Solid Freeform Fabrication Symposium. 2013.