Excerpt from the Proceedings of the COMSOL Conference 2008 Boston

Residual Stresses in a Panel Manufactured Using EBF3 Process

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Abstract: The residual stresses developed in a stiffened panel manufactured using Electron Beam Freeform Fabrication (EBF3) process were studied. EBF3 process is a layer additive process that can be used to build near-net shaped parts directly using computer controlled techniques, which can be used for aerospace structures. A COMSOL model was created to simulate the residual stresses using a thermo-mechanical analysis, with the Goldak's semi ellipsoidal moving heat source. The obtained results indicate that residual stresses are under the yield strength of the material used.

Keywords: Residual stresses, EBF3.

1. Introduction

Developments in rapid manufacturing techniques have made it easier to manufacture objects with complex shapes. One such technique, Electron Beam Free Form Fabrication (EBF3), has promising features of fabricating panels with curvilinear stiffeners. Preliminary research has shown that panels with curvilinear stiffeners might have a reduced weight than panels with straight stiffeners. Thus, it is essential to have a computational design environment (CDE) to obtain optimum design for curvilinear stiffened panels. Currently, the unitized structure group, at Virginia Tech, is working on minimization of EBF3 stiffened panels' mass for buckling, displacements, and stresses constraints for given loading. The EBF3 process widens the placement and sizing optimization of stiffeners. The EBF3 process uses a focused electron beam to create a molten pool on a metallic substrate.

The beam is translated with respect to the surface of the substrate and a metal wire is fed into the pool in layer-additive fashion. The electron beam can be controlled and deflected very precisely and couples very effectively with highly reflective materials. The EBF3 process works with a very finely focused beam that is rastered over a larger pattern to control the size of the molten pool and facilitates capture of the wire. This wire is preheated by the beam, but is not melted until it enters the molten pool [1]. Using the EBF3 technique, virtually any kind of mechanical component can be manufactured regardless the complexity of its shape. In aerospace industry, one of the possible applications is the manufacturing of stiffened panels using curvilinear stiffeners characterized by variable thickness and section shape, directly on the skin of the wing box and fuselage panels of aircrafts. If this technique is validated, it will allow designers to push the limit of structural optimization further than ever possible.

Before introducing EBF3 in the large scale production of stiffened panels, residual stresses caused by the deposition of the material should be evaluated and experimentally validated. Residual stresses can, in fact, compromise the integrity of the structure by decreasing the load carrying capabilities of the components and for this reason it is important to know the value they reach during the manufacturing process.

In this paper, a detailed preliminary analysis of residual stresses developed in a stiffened plate manufactured using EBF3 technology, will be presented for a single layer material deposition. For modelling and coupled analysis of thermal-structural problem a general Finite Element Analysis (FEA) software, COMSOL Multiphysics® is used. It is based upon the finite element method to solve coupled/non-coupled partial differential linear/nonlinear equations (PDE). Generally, the problem is solved by defining the governing equations of the problem, their domains, boundary conditions, initial conditions, parameters and the way they are coupled together.

2. Modeling the problem using COMSOL Multiphysics®

To model the EBF3 process, we chose to analyse the residual stresses generated by the deposition of the first layer of material, while building a full stiffener usually requires 10 to 20 depositions. We assumed that the residual stresses in the plate are mostly due to the deposition of the first layer, which is directly in contact with the plate. The stiffener is straight and is located in the middle of the plate. The material used is Aluminum 2219.
The electron beam requires a vacuum on the order of 6.7×10^{-3} Pa, so the EBF3 process is housed in a large vacuum chamber, which means that there is no convection. As the plate is on a steel table, the bottom of the plate is submitted to conduction, and is considered as a heat sink.

Plate dimensions: 610 x 510 x 2.54 mm

1 layer dimension: 610 x 13 x 1.27 mm

To save CPU time, only half of the plate was modelled, exploiting the symmetry of the geometry, boundary conditions and loads with respect to the YZ plane, as shown in Fig. 1.

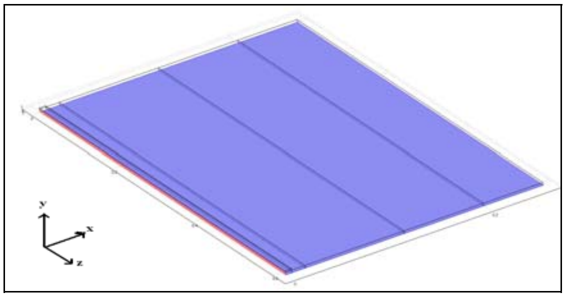

Figure 1: Geometry of the problem; the panel is represented in blue along with the deposited substrate next to the symmetry plane represented in pink.

For calculating residual stresses in the plate, governing differential equations for heat transfer and elastic-plastic structural behaviour are used. The temperature distribution is defined as thermal load for the Stress-Strain analysis. Materials are defined as elastic-plastic, so that when the whole system is cooled back at room temperature, a state of residual stresses is developed.

We implemented the Goldak's semi ellipsoidal moving heat source model, which has been proved very efficient to analyze welding problems.
The equation given by Goldak [2] is the following:

$$Q(x,y,z)=\frac{6\sqrt{3}q_0}{abc\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{a^2}-\frac{3y^2}{b^2}-\frac{3z^2}{c^2}\right)$$

where:

- a, b, c are the parameters of the ellipsoid
- q_0 is obtained by a calibration so that the temperature of deposition is in the range of the melting temperature of Aluminum 2219. It is a function of the mass rate of deposited metal

Here, the moving heat source is along the z-axis, and Q is defined as:

$$Q(x,y,z,t)=\frac{6\sqrt{3}q_0}{abc\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{a^2}-\frac{3y^2}{b^2}-\frac{3(z-vt)^2}{c^2}\right)$$

where v is the speed of the movement.

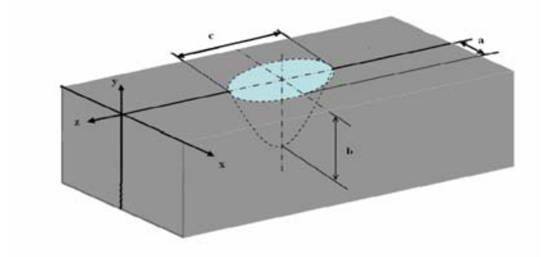

Figure 2: Representation of Goldak's semi ellipsoidal heat source

When the deposition is over, we set

$$Q\left(x, y, z, t \geq t_{dep}\right) = 0$$

where t_{dep} is the time the deposition lasts:

$$t_{dep} = \frac{L_{dep}}{v_{dep}} = \frac{610}{v_{dep}}$$

Parameters used for the analysis:

- a=30mm
- b=30mm
- c=5mm

Those parameters have been chosen based on data presented in [3].

We wanted to see the influence of the thermal convective coefficient on the residual stresses, as we do not know its value.
We decided to test for 500, 1000, 1500 and 2000 W.m^{-2}.K^{-1}

3. Boundary conditions

Thermal boundary conditions

The symmetry plane is thermally insulated. Moreover EBF3 is housed in a vacuum chamber, which means that there is no convection between the plate and the external atmosphere. The plate is supported by a steel table, which is used as a heat sink source. We decided to model the conduction through this steel table by a boundary of high thermal convective coefficient, as it is done in [2]. The thermal heat convection coefficient between a plate of steel and a steel table is 300 W.m^{-2}.K^{-1}
The heat conductivity is 6 times more for aluminum 2219 than for steel, the value of heat convection coefficient needs to be calculated, but we assumed that it was higher than this. Several convective coefficients are tested for EBF3 process.

Mechanical boundary conditions

For the mechanical boundary conditions, the aim is to prevent rigid body motion of the plate, and be as close as possible to the manufacturing process of EBF3. We know that the plate is subjected to bending due to the high difference of temperature between the plate and the deposited layer. We also know that the plate, during the manufacturing, is clamped to prevent this phenomenon.

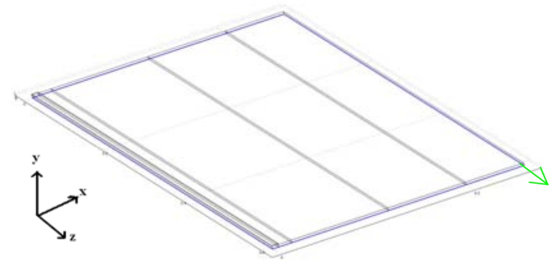

Figure 3: A Y-Z symmetry plane is defined, in green there is one point blocked on the z-direction; the four bottom edges of the plate are blocked in y-direction to prevent bending.

4. Material properties of Aluminum 2219

Density ρ	2831 kg.m^{-3}
Young modulus E	72.4 GPa
Poisson ratio	0.33
Melting range	816-917 K
Convection coefficient h	500 W.m^{-2}.K^{-1}
T_{ref} (room temperature)	293.15 K
Yield Strength at 293,15K	375 MPa

Table 1 : Material properties of Aluminum 2219

While predicting residual stresses, the coupled thermal-structural analysis is carried. During analysis, properties of Aluminum 2219 such as heat capacity, thermal conductivity, coefficient of thermal expansion and yield stress are provided in tabular form as a function of temperature and these are taken from Military Handbook [4].

5. Results and discussions

The results presented below are for a speed deposition of 6.7 mm/s.
Figure 4 presents the moving heat source used to reproduce the deposition of aluminum. The temperature is in the range of melting temperature of the aluminum alloy used (816-917 °K).

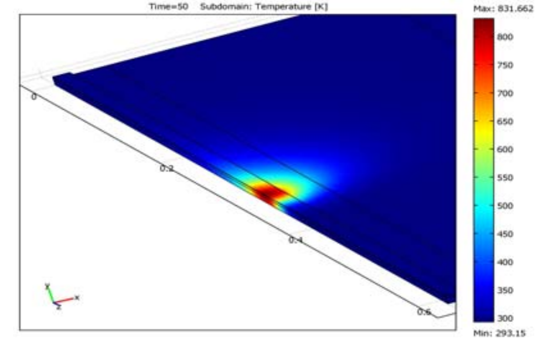

Figure 4: Temperature of the moving heat source at t=50s for v=6.7 mm/s

In Fig. 5, Von Mises stresses in the plate are shown. These results are comparable to those shown in welding analysis papers. For a welding problem on a similar plate with a similar aluminum alloy and a similar welding temperature, our results are in very good agreement [3]. We can notice an increase of the stresses near the boundaries. We do not take this value in account since its high value is only due to boundary effects.

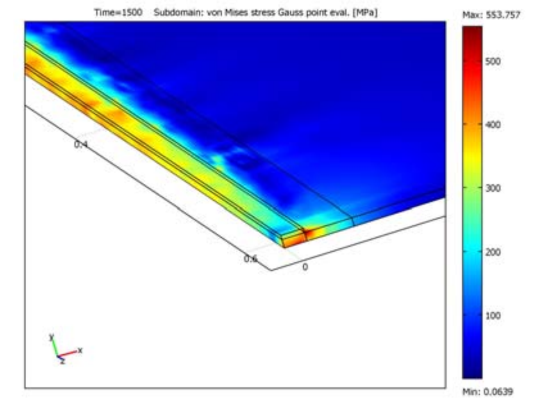

Figure 5: Von Mises stresses at 1500s, when the system is cooled down. The high stresses on the corner are due to boundary effects

In Fig.6, the Von Mises stresses on the surface in the middle of the plate are plotted as function of the distance from the deposition layer. The maximum Von Mises stress value is close, but below the yield stress of Aluminum 2219 which is 375 MPa.

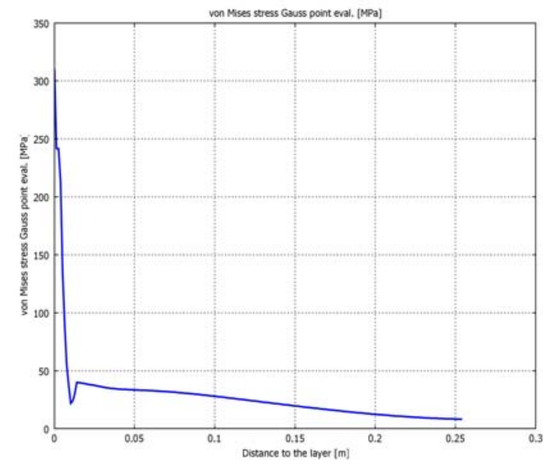

Figure 6: Von Mises stresses vs. the distance from the layer in the middle of the plate. The maximum value reaches 310 MPa.

In Fig.7, theoretical longitudinal residual stresses are represented.

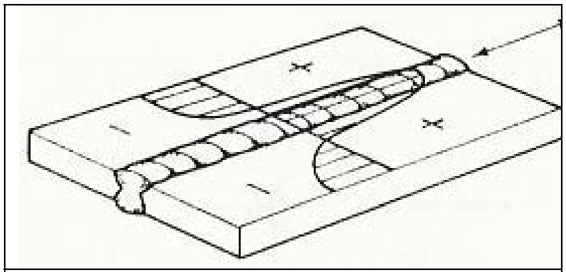

Figure 7: Theoretical longitudinal residual stresses in welded stiffened plates [4]

In Fig.8, we can see the distribution of the longitudinal residual stresses, which matches with the stresses shown in Fig.7.

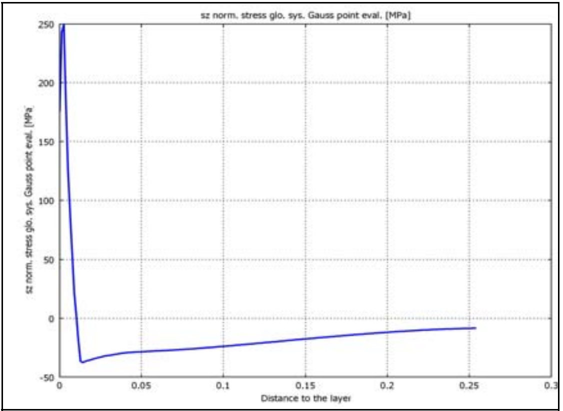

Figure 8: σzz vs. the distance to the layer in the middle of the plate

Fig.9 shows NASA measured Von Mises stresses on a stiffened panel manufactured using EBF3 technology. Although the experimental structure is similar to the modelled panel no data about the measurement process and accuracy were given. In particular the thermal convection coefficient and the rate of deposition of the material, during the experiment, are unknown. Since the value of these two parameters has been proved to have a great influence on the final value of the residual stresses, comparing the analytical results with the measured data should be used only as a qualitative check of the stress distribution.

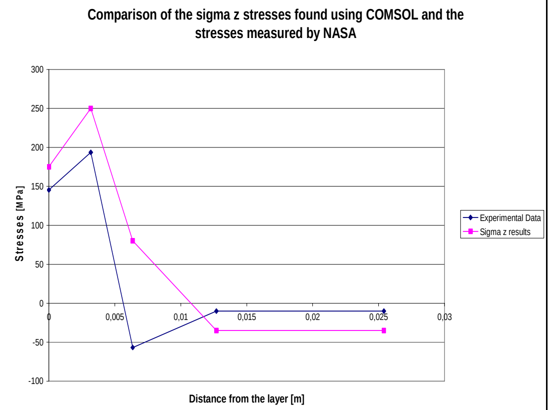

Figure 9 : Comparison of experimental data and COMSOL analysis data

The influence of the convective coefficient value on the maximum value of the Von Mises stresses is limited as Table 2 shows. Nevertheless increasing the value of the convective coefficient tends to decrease the value of the residual stresses and this behaviour could be used to control the stress distribution in the structure during the manufacturing process.

Convective coefficient	Von Mises stresses
500 $W.m^{-2}.K^{-1}$	360 MPa
1000 $W.m^{-2}.K^{-1}$	350 MPa
1500 $W.m^{-2}.K^{-1}$	325 MPa
2000 $W.m^{-2}.K^{-1}$	305 MPa

Table 2: Influence of the convective coefficient on residual stresses

6. Conclusion

In conclusion we can first say that our model is in good agreement with the values found in welding papers [3][5]. This model is a first good approach to the determination of the residual stresses induced by the EBF3 process.

Our models predict little bit higher stresses as compared to those obtained experimentally. Nevertheless these stresses are always below the yield strength of the used aluminum alloy. Experimental measurements of the stresses seem to show a lower level of stress compared to the one calculated in our models. However, for the lack of data about the manufacturing process and the measurements accuracy, we cannot really draw any accurate conclusion on the validity of the analysis.

7. Future work and improvements

Some improvements can be operated to make a model more accurate:

- Getting an accurate convective coefficient, or modelling the steel table under the plate (which will highly increase the computing time)
- Taking in account the micro structural changes, this can have an importance on the values of residual stresses.
- Getting some experimental data about the shape of the weld pool in order to calibrate the parameters of the moving heat source with more accuracy.
- Running an analysis with the deposition of ten layers instead of one, to have an entire stiffener, taking in account each time the residual stresses induced by the former layer.
- Trying different boundary conditions, to be as close as possible to the real manufacturing process. Then if the results are in good agreement with experimental measurements, eventually work on an optimization of the manufacturing process to reduce residual stresses.

With these improvements, an accurate model to predict the residual stresses in the EBF3 process has great chances to be found. Such a model could be very interesting for a future work of optimization. The best speed of deposition, manufacturing conditions (e.g. which edges to clamp? Is clamping the best way to avoid bending and concentrating minimum stresses?), in order to minimise the residual stresses, which can be, as we said, an inconvenient issue.

8. References

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9. Acknowledgements

We thank Dr. Thi Dang and Dr. Nguyen, who helped us during this study by answering promptly our queries and giving us precious and helpful advices. We also would like to thank the Institute for Critical Technology and Applied Science (ICTAS) for use of their facilities. We are thankful to both Ms. Karen Taminger (NASA Langley) and Ms. Cynthia Lach (NASA Langley) for their help. Dr. Kapania would also like to acknowledge the support under NASA contract (NASA NN L08AA02C) with Ms. Karen Taminger as the Program Manager and Ms. Cynthia Lach as the COTR.