INTRODUCTION

Recently, energy beam processing has been widely used in industries to machine difficult to cut materials and produce miniaturized components. The material removal is achieved by increasing the internal energy of atoms in the workpiece, consequently the work material with high internal energy is removed atom by atom, or atom cluster by atom cluster. Thus, this method is able to achieve high machining accuracy [1]. Another significant advantage of the energy beam processing is that there is no limitation imposed by workpiece hardness and ductility. Therefore this technique has a potential to be a new way to machine hard die steels and aeronautical alloys. Among all energy beam processing techniques, the electron beam (EB) process gains more and more attentions nowadays, because the electron beams can be controlled easily and accurately, and their power is generated at a very considerately high-efficiency. Moreover, in most cases, this EB process happens in a vacuum or near vacuum condition, thus the oxidation of the hot workpiece with oxygen is eliminated. Therefore, the EB process has been successfully used for welding, brazing, alloying, and other types of surface treatment [1-4].

Different from the traditional focused EB with a diameter of 0.5mm, the large area plasma-based EB (PBEB) with an effective diameter of 60 mm has been used in this paper. Using this proposed method, it is possible to smooth the workpiece surface of a certain area without beam scanning. The irradiation shot duration is 2-4 µs, so the workpiece can be machined within a very short time. In reference [4], Yu et al found that the machined surface roughness was reduced, and its corrosion resistance and glossiness were greatly improved after PBEB irradiation. However, some craters still exist on the machined surface after PBEB irradiation, which remain a problem for the roughness improvement and quality control of the machined surfaces.

One possible solution is to apply external forces to reduce and eliminate the craters during the melting and solidification process. In mass and fluid transfer community, the external forces are often generated by rotating or oscillating the solid body. The oscillation of the solid body is widely used to introduce an additional relative motion between the fluid and the solid body, thus it leads to an enhancement in the heat and mass transfer during the solidification process [5]. Besides, the oscillation could be an alternative method for removing the liquid condensate. In this study, a new method is proposed to improve the machined surface roughness and reduce the number of cavities by vibrating the worktable during solidification of melted surfaces in PBEB irradiation as shown in Fig. 1. Then, a simulation system using FEM package ABAQUS is developed to verify the proposed solution.

SIMULATION METHODOLOGY

Due to the extremely short EB duration, many difficulties exist in experimental investigation of
electrons and work materials interaction, such as measuring the transient surface temperature, and the moving speed of the solid-liquid interface. The interactions between electrons and work materials are so complicated that it is almost impossible to obtain a realistic analytical solution for them [6]. In addition, the coupled, nonlinear and non-equilibrium processes involved in electrons and material interactions induce an extremely high heating rate and a high temperature gradient. Under these extreme situations, molecular dynamics (MD) simulation, which analyzes the movement of atoms directly, is suitable to investigate evaporation of the melted surface layer in the EBM process [6]. However, due to its prohibitively large computational requirements both in terms of CPU time and memory, it is almost impossible to simulate the solidification process at a micron scale using MD. Thus, the continuum approach will be used to solve the solidification problem after evaporation. When the vibration is applied in the EBM process, thermal/fluid dynamics and mechanical displacement are involved in the solidification, which makes the problem very complicated. Finite element method is used to simulate the solidification process during the vibration assisted PEBE irradiation.

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There are three objectives to use FEM methods to study the vibration assisted solidification during the EBM process. First, with a FEM method, a better understanding will be acquired of the physical phenomena of solidification at a micron-scale. Second, the important solidification processes involving scales that are extremely time consuming to be resolved using MD simulation can be analyzed with continuum-based methods within a reasonable time. More importantly, FEM simulation can verify whether vibration helps to smooth workpiece surfaces in the EBM process.

**SIMULATION OF COUPLED THERMAL-DISPLACEMENT INTERACTION**

As mentioned, thermal/fluid dynamics and mechanical displacement are involved in the solidification, which makes the problem very complicated. In the last meeting report, it has been verified that it is possible to investigate structural and thermal response resulting from the coupling between the melted metal and tank, rather than a detailed solution in the fluid. In this meeting report, the simulation model has been revised to make it more similar to the practical case.

**Problem Description**

From previous experiments, it was found that there were some small cavities observed on the machined surfaces after the EBM process, as shown in Fig. 2. In order to save the computation time, a 2-D coupled thermal-displacement interaction is firstly considered. According to Fig. 2, it can be assumed that the geometry of melted surface is shown in Fig. 3. The model consists of a tank filled with melted metal. The tank measures 2.0 × 0.2 mm, which is filled with 0.15 mm of melted metal. Pure master-slave contact is defined between the tank (master) and the melted metal (slave). The melted metal is subjected to gravity loading. Consequently, an initial geostatic stress field is defined to equilibrate the stresses caused by the self-weight of the melted metal. The tank is modeled as a rigid body and is meshed with R2D2 elements, and a graded mesh of CPE4RT elements is used for the melted metal.

![Micro-cavity](image)

Figure 2. Microscopic view of the machined surface after EBM process.

In this study, the melted metal is considered as an incompressible and viscous fluid material. An effective method for modeling fluid in
ABAQUS/Explicit is to use a simple Newtonian viscous shear model. The shear viscosity also acts as a penalty parameter to suppress shear modes that could tangle the mesh, but a high shear viscosity will result in an overly stiff response. In this paper, the shear viscosity is chosen from the published data.

Figure 3. Diagram of the coupled thermal-displacement interaction problem.

In this paper, the carbon steel is used as the work material, and its mechanical and thermal properties are listed in Table 1. In order to simulate solidification, the latent heat effect was approximated by a sharp increase in heat capacity with a narrow temperature range where phase change takes place. Owing to the difficulties of numerical integration in the phase-change region where the heat capacity has a sharp peak, the enthalpy, which is the integral of the heat capacity with respect to temperature, is used instead in the solution procedure [7, 8]. The shear viscosity of melted metal depends on its temperature, and it is critical to choose an appropriate viscosity-temperature curve for a phase change analysis. The viscosity-temperature curve used in this study is shown in Fig. 4.

Figure 4. Temperature dependent viscosity used in this study.

**Adaptive Meshing**

For problems when large deformations occur, it needs to maintain a high-quality mesh throughout an analysis. Adaptive meshing is such a tool that makes it possible by allowing the mesh to move independently of the material [7, 8]. Adaptive meshing in ABAQUS does not alter the topology (elements and connectivity) of the mesh. Because the fluid flow phenomenon modeled in this example results in large mesh motions, it is necessary to increase the intensity and frequency of adaptive meshing. The frequency value is reduced to 5 increments from a default value of 10, and the number of mesh sweeps used to smooth the mesh is increased to 3 from a default value of 1. In the simulation, sliding boundary regions are used for all contact surface definitions on the melted metal, and the default values are used for all other parameters and controls in ABAQUS for this coupled thermal-displacement interaction problem.

**TABLE 1. Mechanical and thermal properties of the carbon steel.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7893.2</td>
</tr>
<tr>
<td>Thermal capacity (J/Kg-C)</td>
<td>456.0</td>
</tr>
<tr>
<td>Latent heat of fusion (KJ/Kg)</td>
<td>247</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-C)</td>
<td>55.0</td>
</tr>
</tbody>
</table>

**Surface Tension**

The surface tension of liquid metals plays an important role in the rapid solidification at a micron scale. Under normal gravity conditions, surface tension forces contribute significantly to fluid flow (Marangoni or thermo-capillary flows) in solidification processes [9]. However, there is no built-in feature in ABAQUS specifically for surface tension. But it is possible add the surface tension to the melted surface. In a 2-D simulation problem, an edge traction could be used for this function, while a skin with standard membrane element could be added to the free surface in a 3-D simulation domain [7, 8]. Initially, edge tractions are used to handle surface tension in the simulation.

In this study, at first, the edge traction is treated as distributed pressure, which is applied by using the *DSLOAD options. ABAQUS/Explicit also provides a user subroutine *VDLOAD to define the variation of the distributed load magnitude as a function of position for a group of points. In this paper, the non-uniform pressure is defined in the user subroutine VDLOAD. When a pressure load needs to be applied, this subroutine will be called for load integration points associated with each non-uniform load definition.
RESULTS AND DISCUSSION
With the decrease of problem size, the simulation model contains a few very small elements, which will force ABAQUS/Explicit to use a small time increment to integrate the entire model in time. This makes the simulation process very time consuming. By scaling the masses of these controlling elements at the beginning of the step, the stable time increment can be increased significantly, yet the effect on the overall dynamic behavior of the model may be negligible. Unfortunately, when the viscosity is incorporated into the simulation model, the mass scaling technique is not applicable because the shear viscosity is mass dependent. Therefore, it is not possible to use mass scaling method to speed up the simulation process. The only way to improve the computation efficiency is to use high-performance computers. In this paper, a dual core Dell Precision 380 workstation is used for the FEM simulation of the solidification process.

A velocity pulse in the form of a sine wave is prescribed for the tank along the horizontal direction. The vibration conditions used in the simulation are listed in Table 2. From the point of view of fluid dynamics, the assisted vibration generates the shearing forces in the melted area. Assume that the solid target is very large, with a moving speed $v$, and that the melted surface is free to move. If this solid target is moving with certain speed, it causes the melted metal to undergo shear flow. The shear stress is proportional to the velocity gradient of the melted metals. The layer near to the solid target has maximum velocity gradient, so larger shear stress exists in this layer, which takes it to move together with the solid target.

### Table 2. Vibration conditions used in the FEM simulation.

<table>
<thead>
<tr>
<th>Test</th>
<th>Vibration frequency</th>
<th>Vibration amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8000 Hz</td>
<td>5 µm</td>
</tr>
<tr>
<td>2</td>
<td>4000 Hz</td>
<td>10 µm</td>
</tr>
<tr>
<td>3</td>
<td>4000 Hz</td>
<td>5 µm</td>
</tr>
</tbody>
</table>

The simulation analysis mainly focused on the effect of dragging forces and surface tension on smoothing melted surface. In the EBM process, the initial temperature distribution of the heat affected area is firstly estimated as shown in Fig. 5. The melting temperature of the target material is in the range of 1450~1500°C. Target material with a temperature in this range is at a liquid/solid coexistence state, which is also called mushy state, as shown in Fig. 5. When the temperature of target material is greater than 1500°C, its viscosity is quite small. After the temperature decreases to a value lower than 1500°C, its viscosity significantly increases. In the EBM process, the temperature of the melted metal gradually decreases after EB irradiation. Figure 6 (a) shows the temperature distribution after 0.0003 seconds. With the decrease of temperature, the viscosity of the melted surface increases greatly. This increased viscosity results in higher shear stress inside this layer and causes its movement along with the solid target, as shown in Fig. 6 (b). This also causes an increase of moving speed for the lower layer of the heat affected area. While the viscosity of the top layer is still very low because of its high temperature, so limited shear forces are applied to it. Initially the surface tension is the dominant source to smooth the craters on the workpiece surface.

As the solidification process continues, larger shear forces are transferred to top surface. At this time, the dragging forces applied on the top surface together with the surface tension helps to smooth the workpiece surface. As the simulation time reaches 0.0075 seconds, the surface profile and temperature distribution of the melted surface for Test 1 and 2 are presented in Fig. 7. After the same simulation time, the temperature in the heated affected zone for Test 1 is less than that for Test 2. It indicates that the vibration at high frequency is able to improve the heat transfer further during the solidification process. Figure 7 also indicates that the final surface roughness for Test 1 is more uniform than that for Test 2. Therefore, high frequency vibration is a more optimal condition.
Figure 8 shows the average von Mises stress in the target material for two test cases. At high frequency, larger Mises stress is found inside the target material. This is attributed to larger acceleration speed applied on the heat affected area at high frequency. In the vibration assisted solidification process, it is these internal forces that help smooth the craters at the top surface. On the contrary, at low frequency, the lower shear forces are applied on the melted metal in the heat affected area.

In the vibration assisted solidification, the left and right sides of the solid target also oscillate, which pushes the nearby melted metal to move and produces a wave in the melted metal. This may be another reason why the width of the central crater becomes smaller.
In order to investigate the effect of vibration amplitude on the vibration assisted solidification process, one more test is carried out and the simulation results are shown in Fig. 9. From Fig. 7(b) and Fig. 9(a), it can be seen that the final machined surface at low vibration amplitude is more uniform than that at high vibration amplitude. Therefore, high vibration frequency and medium value of vibration amplitude is an optimal vibration condition.

From the simulation result, it is also found that the material at the top surface is solidified when the temperature reduces below its melting point. At this time, the effect of surface tension becomes less and less. Even though, the applied vibration still can transfer some shear forces to the material at the top surface, it is not enough to smooth the top surface any more. Therefore, in order to fully take advantage of the assisted vibration, it is necessary to use the surface tension effect together with the assisted vibration to generate external forces to smooth the top surface when the top surface is still at its liquid state.

CONCLUSIONS

In this paper, a finite element method is used to simulate the vibration assisted EBM process. The simulation result shows that good quality surfaces are achieved when vibration is applied to the worktable. This is attributed to the surface tension and the additional forces applied to the melted metals via vibrating the worktable, which can smooth the workpiece surface. The optimal vibration conditions are found at a medium vibration amplitude and high vibration frequency. Therefore, vibrating the worktable during the EBM process would be a potential solution to eliminate the micro-craters, which are inevitable in the conventional EBM process.

REFERENCES